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A NETWORK MODEL (OSGM-NPS) FOR THE U. S. MARINE CORPS OFFICER STAFFING GOAL PROBLEM

by

James B. Sweeny III

September 1993

Thesis Advisor:	R. Kevin Wood
Second Reader:	G. G. Brown

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A NETWORK MODEL (OSGM-NPS) FOR THE U. S. MARINE CORPS OFFICER STAFFING GOAL PROBLEM

by

James B. Sweeny III
Captain, United States Marine Corps
BS MSCI, Georgia Institute of Technology, 1983

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Author: James B. Sweeny III

Approved by: R. Kevin Wood, Thesis Advisor

G. G. Brown, Second Reader

Peter Purdue, Chairman
Department of Operations Research

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This thesis develops and implements a network linear programming model, called the Officer Staffing Goal Model-NPS (OSGM-NPS), to assist the United States Marine Corps in the peacetime allocation of active duty officers to meet manpower requirements. Due to the Marine Corps' small officer population and diverse range of missions, they are constantly faced with the problem of which officer job positions to fill and which to leave vacant. A set of manning targets, called "staffing goals", is needed to ensure the officer population is efficiently used. Targets are obtained by an "allocation model" (a generalized version of an assignment model) that takes the officer population (supply) and manpower requirements (demand) and returns a solution that fills the most requirements with the most suitable officers. A staffing goal for a billet represents the existence of an officer in the population that can fill that billet. The Marine Corps prioritizes requirements into classes, and unmet requirements within a priority class are shared evenly. OSGM-NPS's computer implementation comprises a group of portable algorithms written in FORTRAN using the elastic transhipment network solver ENET. OSGM-NPS solves the officer staffing goal problem with more requirements filled and unmet requirements more evenly shared than the current mainframe computer model, and it executes in a few minutes on a desktop personal computer making it a less expensive, more accessible model.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The Marine Corps is constantly concerned with the assignment of the right officers to the right jobs. There are never enough qualified officers to fully man the Marine Corps structure, so difficult decisions are made on which positions are filled and which are not. The large size of the officer population and the large number of officer requirements necessitates a computerized model to produce a list of realistic manning targets used in making actual officer assignments. These manning targets are called "staffing goals," and the name of the current computer model that establishes these goals is the Officer Staffing Goal Model (OSGM). OSGM uses computer algorithms developed, executed, and proprietary to a civilian contractor in an obsolete, computer-specific programming language restricting OSGM to an old, off-site mainframe computer.

The computer model developed here, called the Officer Staffing Goal Model-Naval Postgraduate School (OSGM-NPS), states the staffing goal problem as a specialized, network-based linear program. The model aggregates the available officer population, places each officer requirement in one of five priority classes, and determines the eligibility and suitability of aggregate officers for requirements. The solution of OSGM-NPS allocates aggregate officers to meet the maximum number of prioritized officer requirements, while sharing unmet requirements equitably within a priority class. Also, requirements are met with the most suitable officer possible except that a better-suited officer will never be allocated at the sacrifice of the maximum number of requirements

filled. OSGM-NPS can be solved in a few minutes on an 80486 PC. Written in FORTRAN, OSGM-NPS is portable to a myriad of fast, affordable computers.

The results of a comparison between OSGM and OSGM-NPS are: OSGM-NPS fills more of the desired officer requirements than OSGM, and OSGM-NPS shares unmet requirements more equitably. OSGM-NPS costs less to execute than OSGM because OSGM-NPS does not require any leased mainframe computing time.

OSGM-NPS allows the need for staffing goals to dictate when the model is executed. Staffing goals are updated annually, but this could be revised to semiannually or quarterly at no extra cost. The combination of this peacetime staffing goal model with the wartime officer mobilization model already implemented at Headquarters Marine Corps will give the Marine Corps Officer Assignment Branch (MMOA-3) the flexibility and on-site computing power to produce officer staffing goals and mobilization notices without the need or cost of off-site civilian assistance.

I. INTRODUCTION

This thesis describes a pure network linear programming model OSGM-NPS and its implementation to assist the United States Marine Corps in the peacetime allocation of active duty officers to meet manpower requirements, that is, to solve the Officer Staffing Goal Problem. OSGM-NPS fills officer requirements with eligible officers to the maximum extent possible. Requirements cannot always be met so priority classes are modeled so that the highest priority requirements are met first. Additionally, within a priority class, the model ensures that unmet requirements are shared fairly. Furthermore, given that the above constraints are maintained, the model assigns the mix of officers most suited to the requirements. This model is meant as a prototype of a replacement for the current model designed and operated by Decision Systems Associates Incorporated (DSAI).

A. BACKGROUND

The Marine Corps is constantly faced with the problem of assigning officers to billets as best possible. The Marine Corps leadership maintains a force structure that they believe will be adequate for the Marine Corps to fulfill their peacetime mission at an affordable human resource cost, and a force structure for war with little or no consideration for cost. The active duty officer population will never have the necessary mix of grades and skills to fill all the billets of the desired peacetime force structure.

This means that there is not an available officer of the proper grade and skill for every billet in the desired force structure. For this reason, a set of *targets* is needed representing the best way that the officer population can meet the desired manpower requirements. Each manpower requirement is a group of billets. Each target represents a billet that can be filled using the available officer population. These targets are used as goals in the execution of the assignment process where the time and destination for officer transfers is determined. If a billet is currently filled, but there is not a target for the billet, then when the officer in the billet transfers, no effort will be made to replace him. If a billet has a target, then it will be filled if it is empty or it will be kept manned if it is occupied. Since these targets are considered goals for assignments, they are called *staffing goals*.

The assignment process is further complicated by tour length restrictions. To ensure the Marine Corps gets a return on their relocation investment, an officer is usually not allowed to move to another billet until two years after arrival at a new billet. Also, an officer is encouraged to remain at a billet no longer than three to four years so that he may hold a wide range of billets during his career. These tour length restrictions result in an officer being in one of the following three states: He may be eligible for transfer to a new location, restricted to any billet at a specific location, or he may be restricted to a specific billet.

To remain proactive in their assignments, the Marine Corps needs staffing goals to represent the distribution of their future officer population in the future force structure. Most officers transfer in the summer because their children are then out of school.

Therefore, staffing goals are updated annually each summer with the staffing goals representing the best use of the officer population 12 months in the future. The future date, in month and year format, for which staffing goals are made is called the *staffing goal date*. The problem of producing staffing goals is called the Officer Staffing Goal Problem (OSGP) in this thesis.

The solution to the OSGP requires a systematic approach for producing staffing goals. A set of *requirements* is first determined, which are groups of indistinguishable billets. A billet is a position described by skill specialty, location, and pay grade. An example of a requirement comprising two billets is two Majors with the Military Occupational Specialty (MOS) of 0302 (infantry) at Headquarters Marine Corps (HQMC). The primary concern of the OSGP is to *fill* the most requirements possible with the available, eligible officers. Not all requirements will be met, and the solution of the OSGP will determine what portion of the requirements can be filled. The problem is complicated by priority classes of requirements and by *fair sharing* which requires that the pain of unmet requirements be spread out among all the requirements of a priority class. A secondary consideration of the OSGP is to *fit* the officers best suited for a requirement into that requirement. The OSGP is sufficiently large that it requires the assistance of a computer to produce a solution.

The staffing goal process is not an automated assignment system. Staffing goals represent how the officer population can best be distributed among the desired requirements. Assignments are made by the Officer Assignment Monitors, called Monitors, residing at HQMC. They strive to keep their billets filled to the level of the

staffing goals. An officer's eligibility to fill a billet in the OSGP follows the same guidelines used by the Monitors in their assignments. Therefore, a staffing goal represents the existence of an officer in the population who should be available to fill the billet. The actual officer who was allocated in the staffing goal process is of no concern to the Monitor. The Monitor's concern is to keep his billets filled using the officers he controls with consideration for the officer's personal welfare and career advancement. Since the staffing goal process views all officers as nameless faces, each officer's social security number (SSN) is removed in the early stages of processing and retrieved later during reporting after a solution is found. The Marine Corps requires an output file containing a record for each officer in the solution with his SSN and his allocation. Admittedly, they do not use it for any purpose other than validation of staffing goals. If a staffing goal is challenged, the challenger can be shown which officer in the population created the staffing goal.

OSGP has application during wartime as well as peacetime. A wartime officer mobilization computer model was the topic of a Naval Postgraduate School thesis (Rapp, 1987) and a subsequent paper (Bausch, Brown, Hundley, Rapp, and Rosenthal, 1989). One of Captain Rapp's recommendations in his thesis was to incorporate the network optimization techniques used in his thesis into the peacetime staffing goal model. This research uses those techniques as its basis. Since the mobilization process includes all officers on active duty, reservists, and retirees and actually makes assignments, each officer not on active duty being transferred in the mobilization model is sent a mail-gram. This makes the wartime officer mobilization model more of an automated assignment

system than a staffing goal problem. This is why there is a need for two separate models for the peacetime and wartime scenarios.

B. USMC OFFICER STAFFING GOAL OBJECTIVES

The objectives for the OSGP are twofold: Fill manpower requirements to the maximum extent possible and do so with the most desirable officer possible without sacrificing the maximum amount of fill. However, requirements are separated into priority classes where a higher priority class must be filled before a lower priority class, and unmet requirements must be evenly distributed across all requirements in the same priority class.

Fill adheres to Marine Corps staffing policies (MCO 5320.12B, 1991) by specifying which officers are eligible for allocation to which requirements, the priority of a requirement relative to all other requirements, and the distribution of unmet officer requirements among requirements of the same priority. These three policies are explained below.

1. The Marine Corps controls which officers are eligible to fill a requirement by specifying a set of eligibility rules for each requirement. An eligibility rule explicitly describes the characteristics of the officers eligible for that requirement. For example, a requirement (ideally) for one or more Artillery Majors at HQMC will have one rule allowing all Artillery officers with grade Captain through Lieutenant Colonel and another rule that allows any Ground Combat Officer with grade Captain or Major.

2. The priority of a requirement is specified by its *Staffing Precedence Level* (SPL). An SPL is an integer from zero to five (except four) with zero having the highest priority and five the lowest. All requirements within a higher priority SPL must be filled, as much as possible, before requirements in a lower priority SPL are filled.

3. The method by which the problem distributes unmet officer requirements in the same SPL is specified by the *share percent* for each requirement. The share percent is not sufficiently explained either by the Marine Corps or DSAI, therefore, the following two statements are the only guarantee of the share percent's actions in the OSGP.

a. All requirements in an SPL having the same share percent receive the same proportion of fill if possible.

b. Requirements within an SPL having larger share percents receive a larger proportion of the available officers than requirements with smaller share percents.

Each requirement's Staffing Precedence Level is designated in a Marine Corps directive by the Deputy Chief of Staff for Manpower and Reserve Affairs at HQMC (MCO 5320.12B, 1991). The Marine Corps does not specify a share percent which results in the requirement for *fair* sharing of shortages of fill because all requirements are considered to have the same default share percent of 50. The sharing of shortage of fill is also referred to as *proportionate sharing* or *prosharing*.

The secondary OSGP objective, fit, is determined by the Level Number (LN) in the eligibility rules for each requirement (DSAI, 1984). The LN is an integer value greater than zero and less than the maximum allowable number of eligibility rules. It represents a ranking of an eligible officer's suitability to fill a requirement as compared to the suitability of all other officers described by all other rules for the same requirement. For example, if there are five rules for a requirement, each rule's suitability would be ranked from best to worst with the values of one to five respectively. Using the example of the Artillery Majors at HQMC: The rule specifying Artillery

officers with grades Captain to Lieutenant Colonel would have an LN of one and the other rule would have an LN of two because the first rule describes Artillery Officers which are better suited for the requirement.

C. CURRENT STAFFING GOAL PROCESS AND CONCERNS

Officer staffing goals are currently produced by the Officer Staffing Goal Model, an optimization-based heuristic, developed in the mid-1970s by Decision Systems Associates, Incorporated (DSAI). This model, called OSGM-DSAI in this thesis, is executed on a mainframe computer off-site of HQMC at a substantial cost to the Marine Corps. The model solves a sequence of two-step sub-problems with the first sub-problem as the highest priority SPL and all available officers, each subsequent sub-problem adding an SPL, and the last sub-problem incorporating all SPLs. The starting point for each subsequent sub-problem is the previous sub-problem's solution with the requirements of the new SPL added. Step one maximizes the fill of all the requirements in the sub-problem with the available officers, and step two makes exchanges within the solution to achieve a more desirable allocation of the officers while preserving the total fill achieved in the first step (DSAI, 1984, p. 2-25). Fill is controlled by providing eligibility rules, an SPL, and a share percent for each requirement.

Each time the Marine Corps desires to execute OSGM-DSAI they must prepare the input files and send them via modem to the Dallas, Texas site of a privately owned CDC Cyber 175 mainframe computer. The Marine Corps, along with other U. S. Government Agencies, leases computing time from this company. Marine Corps manpower models

are charged a flat fee of $17,500.00 per month for a basic amount of computing resources. If they exceed the basic amount of resources, they are charged a fixed rate per resource unit used. OSGM-DSAI is a small portion of all the manpower models executed for the Marine Corps on this computer. However, for less than one month's leasing costs a powerful desktop computing platform could be purchased for OSGM-NPS allowing the monthly flat fee to be re-negotiated at a lower amount.

The input files are so large that errors are inevitable. Errors that are found when the model is executed are corrected through a series of model executions, phone calls, retransmitting of corrected input files, and model re-execution. Each transmission of the data files takes two to three hours of long distance phone transfer via a modem. All of these factors combine to make OSGM-DSAI a very costly and tedious method of producing staffing goals. The high cost of OSGM-DSAI's execution prevents its use for "what-if" scenarios. It is budgeted for three executions per fiscal year, and therefore, the annual update of staffing goals leaves only two other chances for OSGM-DSAI's use during the rest of the year.

A Commercial Off-the-Shelf (COTS) software analysis was conducted in October 1992 by DSAI investigating the possibility of moving the OSGP onto commercial software using an IBM RS/6000-530 workstation versus continuing to use DSAI's proprietary software algorithms on the CDC Cyber 175 (DSAI, 1992). The report states that the formulation of the *fill* problem as a classical assignment or transportation problem is unacceptable for real-world personnel assignment problems like the OSGP. The report states the shortfalls in the transportation formulation lie in the areas of fill by

priority classes and the distribution of shortages of fill. Full linear programming codes, CPLEX by CPLEX Optimization, Incorporated and OSL (Optimization Subroutine Library) by IBM were evaluated solving a general linear programming formulation of the OSGP, both without success. On large test models the execution times were many hours. DSAI's conclusions were: 256 megabytes of virtual memory on the RS/6000-530 would be insufficient for the OSGP, and execution times of the model would be excessive (larger than 1215 hours which is 50 days). Since the CDC Cyber 175 is over 10 years old, no benchmarks could be found for a computational comparison to an RS\6000-530.

The goals of this thesis are to develop a model to solve the OSGP **exactly**, and provide a flexible implementation that the Marine Corps can operate locally at HQMC on a personal computer to allow more frequent model executions and "what-if" runs at a substantially reduced cost and execution time. The concerns of the COTS software analysis pertaining to the use of a transportation formulation to solve the OSGP will be refuted by developing an elastic network linear programming formulation and using an efficient elastic network solver. A general linear programming formulation and code is unnecessary in solving this problem. The execution times and memory usage in OSGM-NPS will eliminate the concerns of the COTS report.

D. LIMITATIONS OF OSGM-NPS

Certain unused features of OSGM-DSAI are not implemented in OSGM-NPS and the reasons for this must be explained. OSGM-NPS uses the OSGM-DSAI Users Manual (DSAI, 1984) as a guide to the features of the current system. Many features of the

current system are not incorporated into the new system since they are not used by the Marine Corps. An example is attrition rates. Attrition rates are included in OSGM-DSAI to allow it to conduct a Monte Carlo simulation to randomly select officers to remove from the model to account for normal attrition. Currently no simulation is conducted, and the value of such a simulation would be dubious if it were. The actual officers who will leave the Marine Corps prior to the staffing goal date are removed from the input data by the OSGP users, the Officer Assignment Branch MMOA-3 at HQMC. Hence the attrition rate feature is no longer necessary and not included. A complete list of the excluded features is given in Appendix A.

E. OSGM-NPS OVERVIEW

OSGM-NPS is a generalization of the classical transportation model (e.g., Bazaraa, Jarvis, and Sherali, 1990, p. 478). The transportation model moves available supply through a directed bipartite network in the cheapest way to meet demand. There must be enough arcs to allow adequate supply to flow through the network to meet all demand and total supply must equal total demand.

The available active duty officers are aggregated into groups of officers with similar characteristics, called *categories*, and are designated as supply nodes. Manpower requirements are groups of billets and each requirement represents a demand node. Manpower requirements are processed into demand nodes using information contained in the input files. The eligibility rules to connect supply (officer categories) to demand (requirements) are explicitly defined for each demand node in the input files. Each

eligibility rule contains a value that ranks that rule against all other rules for a given demand node. This value becomes the arc cost for all arcs induced by the rule. The combination of the supply nodes, demand nodes, and the eligibility rules with their arcs costs are used to create the bipartite network that is the basic model.

Available supply is rarely sufficient to meet all demand. Together with the restrictive eligibility rules, this necessitates the use of an *elastic* formulation of the transportation model. This formulation allows requirements to be violated by paying a per unit penalty, and allows officers to remain un-allocated by paying a per unit penalty. This elasticity has three desired effects in the model.

1. Flow balance can be violated at a node without the creation of extra nodes and arcs.

2. Unused supply and unmet demand are discouraged while the possibility of exceeding supply and over-filling demand is prevented.

3. Through control of the per unit penalties for unmet demand, fill is executed in SPL order.

The maximum amount of requirements being filled and the prevention of exceeding supply and over-filling of demand are ensured through control of the interactions between the supply and demand node penalties. Greater penalties for not meeting requirements in a higher priority SPL ensures that billets are filled in SPL order. The best fit subject to the maximum fill is achieved by making the arc costs the LN, where the best-suited officers to meet a requirement have a lower LN than those less suitable.

Fill as described thus far is not conducted with fair sharing of shortages. This is accomplished by the creation of another node not included in the basic bipartite network structure. The new node is the origin for a set of arcs connected to the demand nodes (requirements) in need of fair sharing. Each arc represents one element of fill and has a cost that reflects that element's proportional effect on the fill of the demand node as compared to the fill of all other demand nodes in the same SPL. The result is that all nodes within an SPL will share shortages of fill proportionately if completely connected.

Since the OSGM-NPS formulation maintains its network structure, network specific solution methods are available for finding a solution. ENET (Bausch, Brown, Hundley, Rapp, and Rosenthal, 1989), an elasticized version of GNET (Bradley, Brown, and Graves, 1977), is used to obtain an optimal solution to the problem. Both software routines are based on the Network Simplex algorithm which has modest memory requirements and is very fast (e.g., Bazaraa, Jarvis, and Sherali, 1990, p. 432).

All software for OSGM-NPS is written in FORTRAN-77, and is portable to any computer that accepts standard FORTRAN. ENET is a copyrighted product of Insight Incorporated, Alexandria, Virginia. OSGM-NPS was constructed on the AMDAHL 5995-700A Dual Processor System mainframe computer at the Naval Postgraduate School W. R. Church Computer Center using VS FORTRAN from IBM, and currently uses less than 64 megabytes of Random Access Memory (RAM). OSGM-NPS has also been successfully tested on a Compaq 80486 PC with 52 megabytes of RAM. This computing platform for OSGM-NPS had good execution times and the same staffing goal solution as the mainframe prototype.

F. TERMINOLOGY

The officer assignment process, which includes OSGM, abounds with acronyms and unique terminology. The volume of relevant definitions precludes their inclusion in the body of this document. A list of definitions and acronyms is given in Appendix B.

G. OUTLINE

Chapter II discusses the development of the linear programming formulation used to solve the OSGP. Developed in four phases, each phase is discussed along with a listing of its formulation. Emphasis is placed on how the values of the per unit node penalties are the key to OSGM-NPS's adherence to the desires of the Marine Corps, and the development of the proshare arc cost function. Chapter III explains how the OSGP is implemented on a computer as OSGM-NPS, along with the performance of OSGM-NPS versus OSGM-DSAI. Finally, Chapter IV presents conclusions and recommendations for ways the elastic network flow ideas presented herein could be applied to other Marine Corps fill problems.

II. OSGM-NPS FORMULATION

The mathematical formulation for OSGM-NPS is developed in a sequence of four increasingly complex models. In each model, another aspect of the Marine Corps staffing policies is introduced. The development starts with a simple transportation model that maximizes fit and transforms this model into a network model with priority classes and proportionate sharing that still maintains the best fit subject to the maximum fill. The OSGP is essentially a multi-objective optimization problem, but is formulated here as a single objective linear program so that standard linear programming techniques can be used to solve the problem.

A. BASIC TRANSPORTATION MODEL

OSGM-NPS is a generalization of the *transportation model* (e.g., Bazaraa, Jarvis, and Sherali, 1990, p. 478). The transportation model finds the least cost method of transporting a supply of a single commodity from a set of supply nodes to satisfy demands for the commodity at a set of demand nodes. The model is *balanced*, meaning the available supply equals the required demand. The underlying network is denoted $G = (N,A)$ where N is a set of nodes and A is a set of directed arcs which are ordered pairs of nodes (i,j). Furthermore, G is bipartite, meaning that N is partitioned into two subsets N^S and N^D representing the supply and demand nodes, respectively, and where any arc (i,j) has $i \in N^S$ and $j \in N^D$. The traditional transportation model requires that

$G = (N,A)$ be a *complete* bipartite network where an arc $(i,j) \in A$ iff $i \in N^S$ and $j \in N^D$, although this assumption is needlessly restrictive. Each arc (i,j) has a cost per unit flow of c_{ij}, and optimality enters into the model with supply finding the least expensive way to allocate itself through the network G to satisfy demand.

For OSGM-NPS, supply nodes represent officer categories where each category consists of a group of officers possessing the same characteristics. Demand nodes are collections of billets called *requirements*. The supply at node i is s_i and the demand at node j is d_j. If an arc (i,j) exists, then any officer in category i is eligible to fill any billet in requirement j. Since the set of arcs A represents the eligibility specified by the Marine Corps, the network $G = (N,A)$ is called the *eligibility network*. The cost per unit flow on arc (i,j), denoted c_{ij}, is used to represent suitability because each officer in category i is equally suited to hold a position in requirement j. Therefore, if c_{ij} is small, an officer in category i is well-suited for a billet in requirement j, and c_{ij} increases as the officer's suitability decreases. The arc costs are $c_{ij} \in \{0,1,2,3,4,5\}$, where the values one through five are measures of suitability and the value zero is used in special cases where suitability is not a concern. The origin of these values will be discussed in the Arc Generation section of Chapter III. The supply s_i and demand d_j are integer, and the arc costs c_{ij} are integer because of increased computing speed when using integer arithmetic versus floating point arithmetic on most computers.

Let the variable x_{ij} be the number of officers from category i filling a billet in requirement j, i.e. "flowing along" arc (i,j). Since c_{ij} represents the suitability of an officer for a requirement the minimization of $\sum c_{ij}x_{ij}$ in the following linear programming

formulation produces an optimal solution that maximizes fit (e.g., Bazaraa, Jarvis, and Sherali, 1990, p. 481). The following formulation represents a transportation model to solve a simplified version of OSGP called OSGP1.

$$\text{Minimize} \sum_{(i,j)\in A} c_{ij}x_{ij}$$

subject to

$$\sum_{j:(i,j)\in A} x_{ij} = s_i \quad \forall i \in N^S \tag{2.1}$$

$$-\sum_{i:(i,j)\in A} x_{ij} = -d_j \quad \forall j \in N^D \tag{2.2}$$

$$x_{ij} \geq 0 \quad \forall (i,j) \in A$$

If OSGP1 were balanced (i.e., $\sum s_i = \sum d_j$) and the set of arcs A were complete (i.e., there were an arc from each suppiy node to every demand node), then OSGP1 would solve OSGM-NPS. Maximization of fill, prosharing, and fill by priority class would all be moot points because fill would be at 100%. Fit would be maximized because a lower (less expensive) c_{ij} represents a more suitable (better fitting) allocation, and the transportation model finds the least expensive way to allocate supply through the network to satisfy demand. The solution for OSGP1 is integer because the constraint matrix formed by equations (2.1) and (2.2) is a *totally unimodular* matrix (e.g., Bazaraa, Jarvis, and Sherali, 1990, p. 481) and all s_i and d_j are integer. All subsequent

formulations introduced in the following sections will maintain a totally unimodular constraint matrix, thereby guaranteeing an integer solution to OSGM-NPS.

Since OSGP1 is not complete and not balanced, an elastic network model which allows OSGP1's flow balance to be violated while the elastic model remains feasible is needed. This elastic model is called OSGP2, and it is the topic of the next section.

B. ELASTIC NETWORK FLOW MODEL

OSGP1 assumes that the network G is balanced and complete, which is unrealistic for OSGM-NPS. Supply will never equal demand in practice due to the constant entrance and separation of officers, and changes to the Marine Corps structure. Furthermore, the set of arcs A does not represent a complete network, so even if the network were balanced, there might be infeasibility due to the sparseness of the network.

The technique to handle an unbalanced, complete network is to create an extra supply node or demand node along with extra arcs. If $\sum s_i < \sum d_j$, then an extra supply node is created with a supply of $\sum d_j - \sum s_i$ and an arc with a cost of zero is added from the extra supply node to every demand node in the original network. The extra node and arcs allow the original model to be infeasible (i.e., flow balance constraints violated) while the new larger model is feasible (e.g., Nemhauser and Wolsey, 1988, p. 68).

For an incomplete network with $\sum s_i < \sum d_j$, the technique described previously may leave some supply un-allocated causing infeasibility. Therefore, another technique that adds more arcs, in addition to the arcs from the first technique, is needed to allow un-allocated supply to flow through the first technique's extra supply node to a demand

node. An arc is created from each supply node in the original problem to the extra supply node with an arc cost (penalty) to discourage its use. Together, these two techniques combine to allow infeasibility (at a penalty) in an unbalanced and incomplete network.

These techniques increase the number of arcs in the network by the original number of nodes, and hence the number of variables increases by the same amount. This in an inefficient method to ensure feasibility. A more efficient method is to consider flow balance at each node to be *elastic*, and to handle the infeasibility of the network implicitly (Bausch, Brown, Hundley, Rapp, and Rosenthal, 1989). To ensure OSGP1's feasibility without using explicit nodes and arcs, an elastic formulation of the classical transportation model, called OSGP2, is used.

The elastic network flow concept used in OSGP2 allows flow to exceed or fall short of the balanced amount at each node. This concept will be further constrained to only allow flow balance violations in a single direction for each node, resulting in a *semi-elastic* model. This restriction will be implemented in OSGP2 by having very high penalties for the prohibited violations. The concept of full elasticity will be initially introduced, and then the sufficient conditions for the semi-elastic network flow model are derived in general terms.

OSGP2 embellishes the basic transportation formulation with the introduction of elastic variables for each node with their accompanying penalties. Elasticity introduces a pair of non-negative variables z_i^l and z_i^u necessary to maintain flow balance (feasibility) in the original inelastic network model. They represent the necessary flow out of node

i and into node i, respectively. One of the two variables will have a positive value when flow balance at node i, with respect to the original inelastic model, is violated.

The values of z_i^l and z_i^u have different meanings when node i is a supply node versus a demand node. Therefore, the elastic variables are subdivided into those pertaining to supply nodes, z_i^l and z_i^u, and those pertaining to demand nodes, z_j^l and z_j^u. The variable z_i^l represents officers left un-allocated by the model at node i and z_i^u represents imaginary officers created at node i to meet demands. The variable z_j^l represents the filling of imaginary billets at node j and z_j^u represents the unfilled billets at node j.

Each elastic variable has a per unit penalty associated with it. The per unit node penalties determine the effect that elasticity has on the model. Each penalty is a non-negative integer representing the cost per unit increase of the corresponding elastic variable. Let p_i^l, p_i^u, p_j^l, and p_j^u be the per unit penalties for z_i^l, z_i^u, z_j^l, and z_j^u, respectively. Each elastic variable, multiplied by its corresponding per unit penalty, is summed in the objective function. Imaginary officers and billets are not desired for obvious reasons. Therefore, $z_i^u = 0$ and $z_j^l = 0$ must occur for a realistic solution. These two variables are forced to zero by using large per unit penalties which will be derived later, but the variables are still included in the formulation here. The introduction of the elastic variables and their penalties results in OSGP2's formulation below.

$$\text{Minimize} \quad \sum_{(i,j)\in A} c_{ij}x_{ij} + \sum_{i\in N^S} p_i^u z_i^u + \sum_{i\in N^S} p_i^l z_i^l + \sum_{j\in N^D} p_j^u z_j^u + \sum_{j\in N^D} p_j^l z_j^l$$

subject to

$$\sum_{j:(i,j)\in A} x_{ij} = s_i + z_i^u - z_i^l \quad \forall i \in N^S$$

$$-\sum_{i:(i,j)\in A} x_{ij} = -d_j + z_j^u - z_j^l \quad \forall j \in N^D$$

$$x_{ij} \geq 0 \quad \forall (i,j) \in A$$

$$z_i^u,\ z_i^l,\ z_j^u,\ z_j^l \geq 0 \quad \forall\ i \in N^S,\ j \in N^D$$

Restrictions are placed on the node penalties to ensure the following four conditions are satisfied.

1. The creation of imaginary officers is prevented, i.e., z_i^u should be zero.

2. The filling of imaginary billets is prevented, i.e., z_j^l should be zero.

3. Maximum flow through the network G = (N,A) is guaranteed .

4. Maximum fit is guaranteed when there is ample supply to meet demands that are connected to at least one supply node.

The creation of imaginary officers to increase the maximum fill is prohibited. Staffing goals must represent the best use of only the available officer population. In the discussion of this first condition, consider the network in Figure 1.

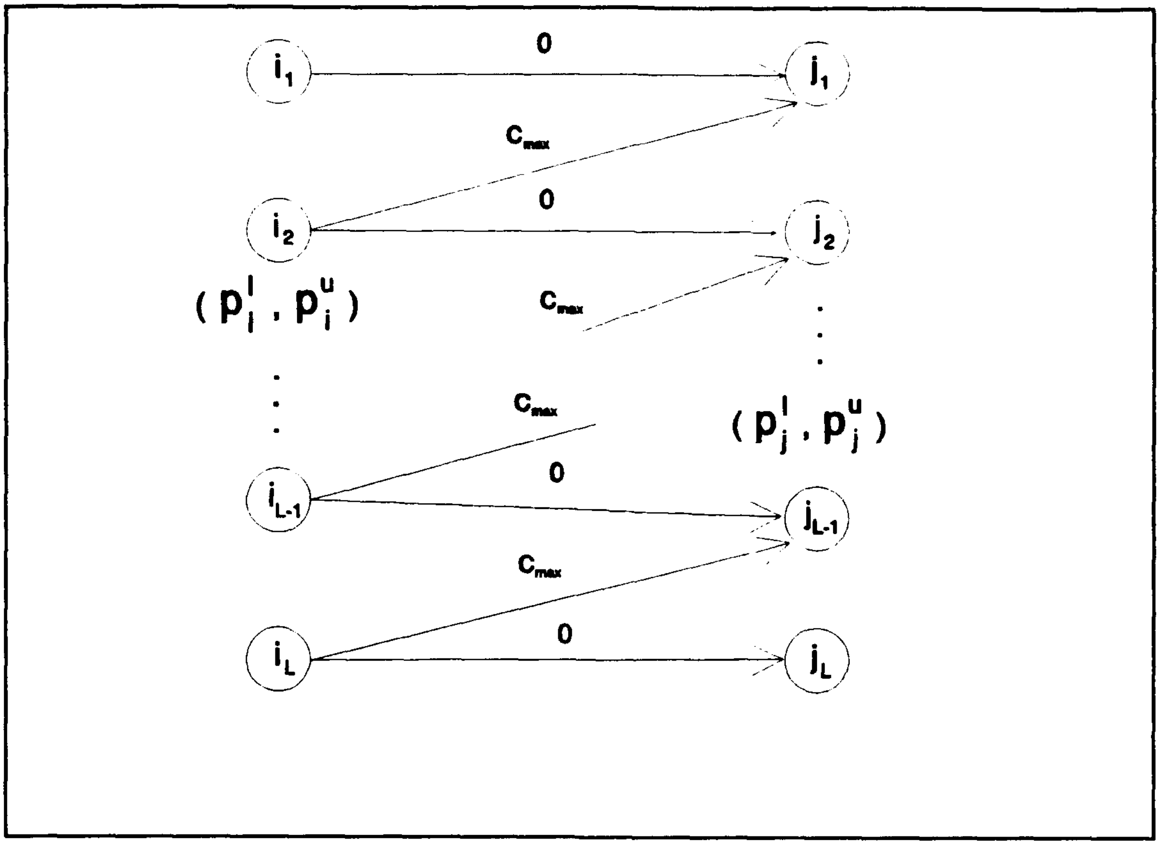

Figure 1. Example Network for the Prevention of Imaginary Officers and Billets.

Suppose (**x**,z) is a feasible set of integer flows to OSGP2. An imaginary officer at node i_1 might be created to meet a demand at node j_L by increasing the flow from i_1 to j_1 by one unit, decreasing the flow from i_2 to j_1 by one unit , increasing the flow from i_2 to j_2 by one unit, etc., until finally increasing the flow from i_L to j_L by one unit. The path from node i_1 to node j_L is called an *alternating path* (e.g., Nemhauser and Wolsey, 1988, p. 611). To ensure that this does not occur, the corresponding change in cost must be positive. Thus

$$c_{i_1,j_1} - c_{i_2,j_1} + c_{i_2,j_2} \cdots + c_{i_L,j_L} + p^u_{i_1} - p^u_{j_L} > 0$$

is necessary, which is true if

$$-(L-1)c_{max} + p_{i_1}^u - p_{j_L}^u > 0$$

where c_{max} is the maximum c_{ij} over all $(i,j) \in A$. The value of L is bounded by the value $L_{max} = \min\{|N^S|,|N^D|\}$, so a sufficient condition to ensure that no imaginary officers are created is

$$p_i^u - p_j^u \geq L_{max}c_{max} + 1 \quad \forall i \in N^S, j \in N^D. \tag{2.3}$$

Similar to preventing the creation of imaginary officers, the filling of imaginary billets must also be prohibited. The filling of an imaginary billet at demand node j is synonymous with having flow into the node in excess of the demand d_j. An examination of the interactions of the node penalties is again required to ensure that this is not allowed.

Using the network in Figure 1, an imaginary billet at node j_L might be filled by a unit of supply from node i_1 by *increasing the flow from* i_1 *to* j_1 *by one unit, decreasing* the flow from i_2 to j_1 by one unit, increasing the flow from i_2 to j_2 by one unit, etc., until finally increasing the flow from i_L to j_L by one unit. To prevent the movement of a unit of supply along the alternating path from node i_1 to node j_L, the corresponding change in cost must be positive, i.e.,

$$c_{i_1,j_1} - c_{i_2,j_1} + c_{i_2,j_2} \ldots + c_{i_L,j_L} + p_{j_L}^l - p_{i_1}^l > 0$$

is necessary, which is true if

$$-(L-1)c_{max} + p^{l}_{j_L} - p^{l}_{i_1} > 0$$

where c_{max} remains the same as above. L_{max} remains an upper bound for L, so a sufficient condition that ensures no imaginary billets are created is

$$p^{l}_{j} - p^{l}_{i} \geq L_{max}c_{max} + 1 \quad \forall i \in N^{S}, j \in N^{D}. \tag{2.4}$$

The maximum flow through the network is of paramount concern as it is the primary objective of the OSGP. Fill is trivially maximized by the structure of OSGP1, but the structure of OSGP1 has been violated by allowing an incomplete and unbalanced network. OSGP2 must ensure that fill is maximized through further restrictions on the values of the node penalties. Consider the network illustrated in Figure 2 in the following discussion of a sufficient condition for achieving a maximum flow.

With the two previously discussed sufficient conditions present, consider two solutions to the network in Figure 2: The first is when all the diagonal arcs (i_k,j_{k-1}) are used, and the second when all the horizontal arcs (i_k,j_k) are used. The first solution leaves an unused unit of supply at node i_1 and an unfilled demand at node j_L, whereas the second solution allocates every officer and fills every billet. The second solution represent maximum fill, and is preferred over the first solution when the corresponding change in cost between the solutions is positive. Thus

$$c_{i_2j_1} - c_{i_1j_1} + c_{i_3j_2} - c_{i_2j_2} + \ldots + c_{i_Lj_{L-1}} - c_{i_Lj_L} + p^{l}_{i_1} + p^{u}_{j_L} > 0$$

is necessary, which is true if

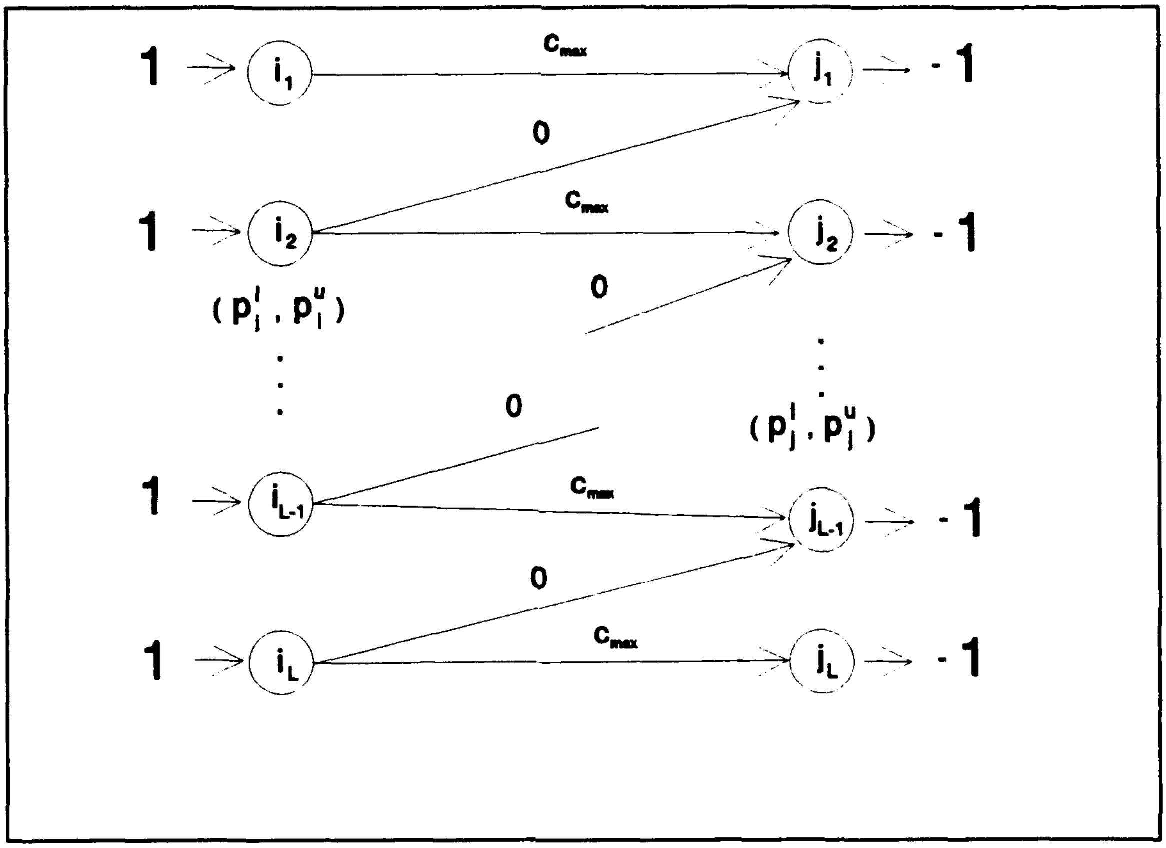

Figure 2. Maximum Flow Condition.

$$-(L-1)c_{max} + p_{i_1}^l + p_{j_L}^u > 0$$

where c_{max} is the same as before. The value L remains bounded by L_{max}, so a sufficient condition to ensure that maximum fill (maximum flow) is always achieved is

$$p_i^l + p_j^u \geq L_{max}c_{max} + 1 \quad \forall i \in N^S, j \in N^D. \tag{2.5}$$

In the derivation of the sufficient condition for maximum flow (fill), the first solution to the network in Figure 2 used all arcs (i_k, j_{k-1}), and represented the maximum fit for the network. The sufficient condition for maximum flow in equation (2.5) ensured the second solution using arcs (i_k, j_k) was chosen. Therefore, greater fill is always

preferred over a better fit. However, the best fit when there is plenty of supply to meet demand is not considered in the sufficient condition for maximum flow. This situation is considered below.

When there is ample supply to meet demand adjacent to at least one supply node (called *connected demand*) the most suitable (best fitting) officer for each billet must be allocated. Ample supply implies that $z_j^u = 0 \; \forall \; j \in N^D$. With all three of the sufficient conditions previously discussed present and ample supply to meet connected demand, the penalties p_i^l and the arc costs in OSGP2's objective function determine fit.

Fit was maximized in OSGP1 by the suitability of an officer being represented in the arc costs and the minimum cost flow structure of the transportation model. This meant that the least cost (best fitting) officers possible were allocated to a demand subject to the fact that all officers were allocated (maximum fill). In OSGP2 p_i^l and p_j^u are the penalties for not sending a unit of flow along an arc (i,j). In the situation where there is ample supply to meet connected demand, the demand node penalty p_j^u does not affect the model because $z_j^u = 0$. Therefore, the penalty p_i^l represents the cost of not sending an available unit of supply along an arc (i,j), and a supply node with a larger p_i^l would have its supply allocated with a higher priority than a supply node with a smaller p_i^l. To allow the arc costs to solely determine fit, these penalties p_i^l must be the same for all supply nodes. Therefore, a sufficient condition that ensures fit (as defined by the arc costs c_{ij}) is maximized when there is ample supply to meet connected demand is

$$p_i^l = p_{i'}^l \quad \forall\ i, i' \in N^s. \tag{2.6}$$

Through control of the penalties for the elastic variables, as shown in the sufficient conditions in equations (2.3), (2.4), (2.5), and (2.6), the OSGP2 formulation provides a realistic solution satisfying the Marine Corps objectives of maximizing fill and fit with fill having priority over fit in a network where $\sum s_i \neq \sum d_j$ and G is sparse. OSGP2 treats each requirement equally in its search to maximize fill. No billet is considered more important than another. However, the Marine Corps prioritizes their requirements and insists that fill in high priority requirements not be sacrificed to improve fill in a lower priority requirement. By changing only the penalty structure in the OSGP2 formulation, the next section describes how this priority feature is achieved in the OSGP3 model.

C. ELASTIC NETWORK FLOW MODEL WITH PRIORITY CLASSES

The Marine Corps divides their manpower requirements into priority classes allowing the Marine Corps leadership to influence the staffing goal process by specifying which requirements are more important than others. Marine Corps policy is that no lower priority requirement will be met at the expense of a higher priority requirement, and that lower numbered classes have the higher priority. Manipulation of the upper demand node penalties, p_j^u, $j \in N^D$, without a modification to the OSGP2 formulation, will create the new model OSGP3 that will conduct fill in priority class order.

Let the priority classes be represented by the ordered set $K = \{1,2,\ldots,\kappa\}$, and the set of demand nodes N^D be partitioned into exhaustive disjoint subsets $N_1^D, N_2^D, \ldots, N_\kappa^D$.

To motivate OSGP3 to meet higher priority demands first, the penalty for not meeting a demand in a higher priority class must be greater than the analogous penalty for a lower priority class, i.e. $p_j^u > p_{j'}^u$ for $j \in N_k^D$ and $j' \in N_{k'}^D$ where $k' > k$. The fact that the penalties p_j^u are scaled according to their priority class is a necessary condition for the model to fill the higher priority demands first, but it is easy to show by example that it is not sufficient.

Using Figure 1 from the previous section, the unmet demand penalties between classes must be set so that given a set of feasible flows (x,z), OSGP3 will not sacrifice a unit of met demand at node j_1 to meet a unit of demand at node j_L where $j_1 \in N_k^D$, $j_L \in N_{k'}^D$, and $k' > k$. Using the alternating path idea again, demand at node j_1 will not be sacrificed for demand at j_L if

$$-c_{i_2,j_1} + c_{i_2,j_2} \ldots -c_{i_L,j_{L-1}} + c_{i_L,j_L} + p_{j_1}^u - p_{j_L}^u > 0$$

which is true if

$$-(L-1)c_{max} + p_{j_1}^u - p_{j_L}^u > 0$$

where c_{max} is defined as before. Using L_{max} as before, the following sufficient condition ensures fill in priority order.

$$p_j^u - p_{j'}^u \geq L_{max}c_{max} + 1 \quad \forall\, j \in N_k^D;\; j' \in N_{k'}^D;\; k' > k \qquad (2.7)$$

OSGP3 consists of the formulation for the OSGP2 model with new restrictions on the upper demand node penalties p_j^u, $j \in N^D$. OSGP3's solution has the maximum demand filled in priority class order with the most suitable officer satisfying demand

subject to the maximum fill. All of the Marine Corps' objectives are fulfilled except fair sharing shortages of fill among all demand nodes in the same priority class. The next section introduces the final model, OSGP4, that will incorporate all of the features desired in OSGM-NPS.

D. ELASTIC NETWORK FLOW MODEL WITH PRIORITY CLASSES AND PROSHARING

Equity is a key concept in Marine Corps manpower processes where all staffing decisions should be made in an unbiased manner. Fair sharing of shortages of fill across demand nodes of the same priority class ensures an equitable distribution of staffing goals that do not cover the desired manpower requirements. Fair sharing is introduced in OSGP4 in such a way as not to violate any of the objectives achieved in OSGP3.

The network structure must be slightly modified to incorporate prosharing. An extra node, called a *dummy* node, is introduced with the symbol δ. The dummy node is the tail node of a set of directed *proshare arcs* $(\delta,j) \in A^P$ with their head nodes being the demand nodes in need of proportionate sharing. There is a proshare arc entering demand node j with a capacity of one for every element of demand d_j, with a cost that reflects that arc's proportional contribution to the demand node's fill relative to the fill of all other demand nodes in the same priority class. These proshare arc costs for demand node j are calculated using a set of increasing linear functions, one for each priority class k, with each function having a range unique to its priority class.

The new network, which includes prosharing, $G' = (N',A')$ is represented by a set of nodes N' where $N' = N \cup \{\delta\}$, and $A' = A \cup A^P$. The network $G' = (N',A')$ is called the *model network* as it is the final version of the OSGP that solves OSGM-NPS. Prosharing is conducted within a priority class and always for every demand node within a class, but not necessarily for all classes. Therefore, let the set $K^P \subset K$ be the priority classes where prosharing is conducted. The index a, with values $\{1,2,\ldots,d_j\}$, represents the a^{th} proshare arc $(\delta,j) \in A^P$, from δ to demand node j. The cost of the a^{th} proshare arc for demand node j is h_{aj}, and the variable y_{aj} represents the flow along the a^{th} proshare arc $(\delta,j) \in A^P$ for demand node j. The derivation of the h_{aj} will be delayed until the model is formulated.

OSGP4 introduces a special case officer category where officers are all restricted in allocation to a specific billet. Each officer in a special category must be allocated to a specific billet or he remains un-allocated by the model. Let $A^F \subset A$ be the set of fixed arcs (i,j) from special officer category i to requirement j, and let f_{ij} be the desired amount of fixed flow along arc $(i,j) \in A^F$. To ensure the proper allocation is made, the following occurs: When an arc $(i,j) \in A^F$ is generated, the arc must have non-zero lower and upper bounds l_{ij} and u_{ij}, where $l_{ij} = u_{ij} = f_{ij}$. This special case introduces flow bounds into OSGP4, with the bounds on all arcs $(i,j) \in A'$ separated into three groups: the default bounds, proshare arc bounds, and arc flow bounds for the special case outlined above. The default bounds are $(l_{ij},u_{ij}) = (0,\Sigma s_i)\ \forall\ (i,j) \in A - A^F$, the proshare bounds are $(l_{\delta j},u_{\delta j}) = (0,1)\ \forall\ (\delta,j) \in A^P$, and the special case bounds are $(l_{ij},u_{ij}) =$

$(f_{ij}, f_{ij}) \ \forall\ (i,j) \in A^F$. The following equations incorporate these modifications to produce a formulation for the OSGP4 model.

$$\text{Minimize} \sum_{(i,j)\in A} c_{ij}x_{ij} + \sum_{i\in N^S} p_i^l z_i^l + \sum_{i\in N^S} p_i^u z_i^u + \sum_{j\in N^D} p_j^l z_j^l$$
$$\sum_{j\in N^D} p_j^u z_j^u + \sum_{k\in K^P}\sum_{j\in N_k^D}\sum_{a=1}^{d_j} h_{aj}y_{aj} + 0\,z_\delta^l + 0\,z_\delta^u$$

subject to

$$\sum_{j:(i,j)\in A} x_{ij} = s_i + z_i^u - z_i^l \quad \forall i \in N^S$$

$$-\sum_{i:(i,j)\in A} x_{ij} = -d_j + z_j^u - z_j^l \quad \forall j \in N_k^D, k \in K - K^P$$

$$-\sum_{i:(i,j)\in A} x_{ij} - \sum_{a=1}^{d_j} y_{aj} = -d_j + z_j^u - z_j^l \quad \forall j \in N_k^D, k \in K^P$$

$$\sum_{k\in K^P}\sum_{j\in N_k^D}\sum_{a=1}^{d_j} y_{aj} = s_\delta + z_\delta^u - z_\delta^l \tag{2.8}$$

$$0 \le y_{aj} \le 1 \quad \forall j \in N^P, a = \{1, 2, \ldots, d_j\}$$

$$z_i^u,\ z_i^l,\ z_j^u,\ z_j^l \ge 0 \quad \forall\ i \in N^S,\ j \in N^D$$

$$l_{ij} \le x_{ij} \le u_{ij} \quad \forall (i,j) \in A$$

The values of s_δ, p_δ^l, and p_δ^u are zero allowing δ to be a totally unconstrained node with the capability of producing as many units of flow as necessary to artificially meet demand

while producing the proshare effect. (In fact, equation (2.8) may be omitted in the formulation, but is included since the elastic network solver requires that it be defined.)

The prosharing effect is created by the proshare arc costs h_{aj}. These costs must be designed to cause prosharing and not destroy any features of the previous formulations. The direction of flow of a proshare arc is from δ into node j. A positive value of an elastic variable z_j^u can be thought of as flow into node j to preserve flow balance (feasibility). Both of these items provide flow in the same direction for demand node j. A proshare arc (δ,j) with bounds $(l_{\delta j},u_{\delta j}) = (0,1)$ is created for every unit of demand at node j, so a fill shortage of one could be met by either a unit of flow along a proshare arc or a unit increase in the elastic variable z_j^u. Prosharing is caused by the proshare arcs providing all the flow necessary to meet shortages at node j such that $j \in N_k^D$ and $k \in K^P$, versus using the elastic variable z_j^u. Therefore, every proshare arc costs in priority class k must satisfy the conditions $h_{aj} < \rho_j^u$ for $j \in N_k^D$ to ensure they are used versus z_j^u, $j \in N_k^D$. (At this point the z_j^u are superfluous, but must be dealt with since they and their penalties are always defined in the solver to be used.) The penalties for z_j^u cause fill in priority class order by the sufficient condition set in equation (2.7). Therefore, the proshare arc costs must adhere to a similar condition. Intuitively, fair sharing is created by having the cost to not meet the a^{th} unit of demand d_j at node j be the same as the a'^{th} unit of demand $d_{j'}$ at node j', where $(a/d_j) \approx (a'/d_{j'})$ represents the same proportion of fill. This concept is developed below.

Prosharing is driven by the proshare arc costs. Therefore, the creation of an arc cost function f(), is of great importance. Let x_j be the *real* flow into demand node j,

where real flow is flow from the supply nodes in the set N^S versus flow from the dummy node. The measure of interest is the deviation of x_j from d_j, $(d_j - x_j)$, but a deviation of two from a node with demand four should not carry the same *weight* as a deviation of two from a node with demand eight. Consider the simple problem with a single supply node with supply S.

$$\text{Minimize} \sum_{j \in N_k^D} \frac{(d_j - x_j)^2}{d_j} \tag{2.9}$$

$$\sum_{j \in N_k^D} x_j \leq S \tag{2.10}$$

With the dual variable u for the constraint in equation (2.10), the Kuhn-Tucker Conditions for this problem result in the following equation (e.g., Bazaraa and Shetty, 1979, p. 146).

$$u = \frac{-2d_j + 2x_j}{d_j}$$

which implies

$$\frac{-2d_{j'} + 2x_{j'}}{d_{j'}} = \frac{-2d_j + 2x_j}{d_j} \quad \forall\, j, j' \in N_k^D$$

or, more simply

$$\frac{x_{j'}}{d_{j'}} = \frac{x_j}{d_j}. \tag{2.11}$$

Equation (2.11) is the sufficient condition for optimality for fair sharing.

Fair sharing unmet demand focuses on the shortages of fill at node j, therefore, the proshare arc cost function can be derived using $y_j = (d_j - x_j)$ which is the unmet demand at node j. Equation (2.9) becomes the following.

$$\text{Minimize} \sum_{j \in N_k^D} \frac{y_j^2}{d_j} \tag{2.12}$$

The penalty condition preventing fill in excess of demand in equation (2.4) makes $y_j \geq 0$. The piece-wise linear approximation to equation (2.11) is

$$\text{Minimize} \sum_{j \in N_k^D} \sum_{a=1}^{d_j} \frac{2a}{d_j} y_{aj} \tag{2.13}$$

$$0 \leq y_{aj} \leq 1 \quad \forall\ j \in N_k^D,\ a = \{1, 2, \ldots, d_j\}.$$

Thus, the proshare arc cost structure is based on the proportion of the demand met (or missed) at a node j. This arc cost structure supports the intuitive proposition made for fair sharing because it weights each proshare arc cost by its proportional contribution to the fill of the demand node.

Equation (2.13) shows the basic structure of the proshare arc function for a single priority class. OSGP4 has multiple priority classes and must adhere to OSGP3's progress in model development. Control over the range of the proshare arc cost function is necessary to maintain the features of OSGP3. Let $f_k(a,j) = \alpha_k(a/d_j)$ be the structure of the proshare arc cost function for priority class k, and let its range be $[\gamma_k, \alpha_k]$. Define $h^k_{min} = \gamma_k$ and $h^k_{max} = \alpha_k$, and let d^k_{max} be the largest demand in priority class k. The

prioritized fill effect in OSGP3 ensured by equation (2.7) will be achieved with the following conditions in OSGP4.

$$h_{min}^{k} - h_{max}^{k+1} \geq L_{max} c_{max} + 1 \tag{2.14}$$

along with the minimum proshare arc cost of

$$h_{min}^{\kappa} = \frac{h_{max}^{\kappa}}{d_{max}^{\kappa}} = L_{max} c_{max} + 1\,. \tag{2.15}$$

A sufficient condition for the proshare arcs to be used versus the elastic variables for unmet demand in class k is

$$p_j^u = h_{max}^{k} + 1 \ \forall j \in N_k^D, k \in K^P. \tag{2.16}$$

With these sufficient conditions the following equation produces the proshare arc cost for priority class k.

$$f_k(a,j) = h_{aj} = h_{max}^{k} \lfloor \frac{a}{d_j} \rfloor \ \forall j \in N_k^D, \ k \in K^P \tag{2.17}$$

In the course of describing the four models OSGP1 through OSGP4 resulting in a model that solves OSGM-NPS, the following sufficient conditions exist to ensure the model has the necessary features to solve the OSGP in accordance with Marine Corps staffing policies. These conditions are summarized to provide an overall scope of the input data unique to OSGM-NPS required for its solution to the OSGP.

1. Sufficient Condition 1: Prevent the creation of an imaginary officer in equation (2.3).

$$p_i^u - p_j^u \geq L_{max} c_{max} + 1 \quad \forall i \in N^S, j \in N^D$$

2. Sufficient Condition 2: Prevent the filling of an imaginary billet in equation (2.4).

$$p_j^l - p_i^l \geq L_{max} c_{max} + 1 \quad \forall i \in N^S, j \in N^D$$

3. Sufficient Condition 3: Guarantee maximum flow through the network in equation (2.5).

$$p_i^l + p_j^u \geq L_{max} c_{max} + 1 \quad \forall i \in N^S, j \in N^D$$

4. Sufficient Condition 4: Guarantee maximum fit when there is ample supply to meet demand in equation (2.6).

$$p_i^l = p_{i'}^l \quad \forall\, i, i' \in N^S$$

5. Sufficient Condition 5: Ensure fill is conducted in priority class order without proportionate sharing in equation (2.7).

$$p_j^u - p_{j'}^u \geq L_{max} c_{max} + 1 \quad \forall\, j \in N_k^D;\ j' \in N_{k'}^D;\ k' > k$$

6. Sufficient Condition 6: Ensure the proshare arc costs do not conflict with prioritized fill in equation (2.14).

$$h_{min}^k - h_{max}^{k+1} \geq L_{max} c_{max} + 1$$

7. Sufficient Condition 7: Ensure that fair sharing is conducted within a single priority class in equation (2.15)

$$h_{min}^{\kappa} = \frac{h_{max}^{\kappa}}{d_{max}^{\kappa}} = L_{max} c_{max} + 1$$

8. Sufficient Condition 8: Ensure the proshare arcs bear the burden of supplying the necessary flow into demand nodes to maintain model feasibility in equation (2.16).

$$p_j^u = h_{max}^k + 1 \quad \forall j \in N_k^D, k \in K^P$$

9. Sufficient Condition 9: Conduct fair sharing of shortages of fill within a priority class by using the proshare arc cost function in equation (2.17).

$$f_k(a,j) = h_{aj} = h_{max}^k \left\lfloor \frac{a}{d_j} \right\rfloor \quad \forall j \in N_k^D, \; k \in K^P$$

Since the proshare arc costs and node penalties for priority class k are dependent upon those of the next lower priority class k+1, they are produced in a cascading fashion with a simple algorithm, called PENGEN, from the lowest priority class (class κ) to the highest priority class, class one. The output from PENGEN is the set of necessary elements to create each node's penalties and the proshare arc costs during the construction of the network discussed later. OSGM-NPS conducts prosharing in all priority classes except the highest priority class of one. The following notation is necessary for the algorithm.

1. Let the value $P^u(k)$ be the upper demand node penalty for priority class k.
2. Let the value P_D^l be the lower demand node penalty for all demand nodes.
3. Let the values P_S^l and P_S^u be the lower and upper supply node penalties.

Algorithm PENGEN:

Input: N^S, N^D, K, c_{ij}, d_j
Output: p_i^l, p_i^u, p_j^l, and a p_j^u and h_{max}^k for each $k \in K^P$
{$L_{max} = \min \{|N^S|, |N^D|\}$;
$c_{max} = \max_{(i,j) \in A} c_{ij}$;
$INC = L_{max} \times c_{max} + 1$;
$P_0 = 0$;
For $k = \kappa$ down to 2 {
    $h_{min}^k = P_0 + INC$; {Sufficient Conditions 6 and 7}
    $d_{max}^k = \max \{d_j\} \ \forall\, j \in N_k^D$;
    $h_{max}^k = h_{min}^k \times d_{max}^k$; {Sufficient Condition 7}
    $P^u(k) = h_{max}^k + 1$; {Sufficient Condition 8}
    Print ("For all demand nodes j in class ",k,": p_j^u = ",$P^u(k)$);
    Print ("For priority class ",k,": h_{max}^k = ",h_{max}^k);
    $P_0 = P^u(k)$;
    }
$P^u(1) = P_0 + INC$; {Sufficient Condition 5}
$P_S^l = P^u(1) + 1$; {Sufficient Condition 3}
$P_D^l = P_S^l + INC$; {Sufficient Condition 2}
$P_S^u = P^u(1) + INC$; {Sufficient Condition 1}
Print("For all demand nodes j: p_j^l = ",P_D^l);
Print("For all supply nodes i: p_i^l = ",P_S^l); {Sufficient Condition 4}
Print("For all supply nodes i: p_i^u = ",P_S^u);
}

The OSGP4 model meets all of the objectives of OSGM-NPS using the described cost and penalty structure. Each billet filled becomes a staffing goal, and each officer flowing along an arc $(i,j) \in A$ represents an eligible officer from category i occupying a billet in requirement j. Furthermore, category i is the best suited category available to provide an officer for a staffing goal in requirement j under the condition that maximum fill is still achieved. With approximately 17,000 officer and 15,000 billets, which become 11,000 supply nodes and 7,000 demand nodes, the problem is obviously too large for any solution method that does not use a computer. The implementation of OSGM-NPS's formulation developed in this chapter is the topic of the next chapter along

with computational results and a comparison of these results with OSGM-DSAI's performance.

III. COMPUTER IMPLEMENTATION AND RESULTS

OSGM-NPS's formulation is an elastic network linear program, which could be converted into a standard pure network linear program. Therefore, one of the many minimum cost flow network algorithms is appropriate for its implementation. These specialized algorithms are much faster than more general linear programming solution techniques. The choice of solver for this thesis is ENET which comes from the GNET family of primal network linear programming solvers. ENET is specifically designed to handle the elastic variables as used in OSGM-NPS. OSGM-NPS consists of three modules, the model generator, the solver (ENET), and the report writer. All coded in FORTRAN-77, they process the data from three input files into a network representation, solve the elastic network flow model, and then produce output files required by the Marine Corps.

A. INPUT FILES

There are three input files for OSGM-NPS, the Authorized Strength Report (ASR) File, the Manpower Management System (MMS) Extract, and the Dictionary File. The ASR File and MMS Extract File are outputs of other manpower computer systems at HQMC, and MMOA-3, the user of OSGM, produces the Dictionary File. In essence supply comes from the MMS Extract File, demand stems from the ASR File, and the eligibility network G is defined by the eligibility rules in the Dictionary File which

determine whether or not $i \in N^S$ and $j \in N^D$ may be connected by an arc (i,j). Each of these files is briefly described below.

1. AUTHORIZED STRENGTH REPORT FILE

The ASR file contains the list of demands for officers that the Marine Corps needs to carry out their peacetime mission. Each non-zero entry in the file represents a requirement. Each requirement is a collection of billets defined by a billet grade (BGRD), billet Military Occupational Specialty (BMOS), billet Monitored Command Code (BMCC), and authorization. The BGRD is the rank or relative status of the officer necessary for the billet, the BMOS is the skills required for the billet, the BMCC is the location of the billet, and the authorization is the number of billets required to be filled. A typical requirement of five billets the Marine Corps would like to meet is five Captain (BGRD 3) Infantry Officers (MOS 0302) at First Battalion, Second Marine Regiment, Second Marine Division, Camp Lejeune, North Carolina (MCC V12). Consequently, the ASR file has a list of requirements (which may not be fillable) defined by BMCC, BMOS, BGRD, and authorization.

2. MMS EXTRACT FILE

The MMS Extract File lists all of the officers in the Marine Corps, except that it has been processed to remove officers that will leave the Marine Corps prior to the staffing goal date. The officers in the file represent the available disaggregated supply to meet the demands described previously in the ASR File. OSGM-NPS aggregates officers into categories (supply nodes) based on the following information:

Primary MOS (PMOS), first and second Additional MOSs (unordered), pay grade, experience level (experienced or unexperienced), duty limitation (limited duty officer or unrestricted), sex, duty status (active, reserve, or retired), and movement status (allowed to move or restricted). All officers in a category are considered equally eligible and suitable to fill a billet given the values of the ten characteristics on which aggregation is conducted. Each officer's SSN is stored by the model for use during report writing.

3. DICTIONARY FILE

The Dictionary File consists of 11 types of information that the model user provides to control the execution of OSGM-NPS. This file is the only way the Marine Corps can manipulate the staffing goal process because the other two files represent fixed data which is not easily manipulated. The Dictionary File contains the information listed below:

1. A list of all the valid MOSs and their MOS types.
2. A list of critical MOSs in need of a very high priority classification.
3. Information to make modifications to the ASR File.
4. Information to process the modified ASR File into demand nodes.
5. The list of eligibility rules.
6. A list of training requirements.
7. A list of MCCs that are training commands.
8. Information for modifying the officer categories.
9. A list of command titles and their MCCs for use in reports.

Each record in the Dictionary file contains a two digit identification code (e.g., B1 or E2). This identifier delineates the 11 record types and an asterisk denotes a comment record.

B. MODEL GENERATOR

A discussion of the model generator is necessary to relate the topics discussed in OSGM-NPS's formulation to its computer implementation. The model generator conducts two major tasks, processing the input files and generating the model network $G' = (N',A')$. The generation of the model network is conducted in two segments, node list generation and arc list generation. Node list generation is discussed below with the processing of input data, and arc list generation is considered in its own section. Processing of the input files is conducted in the following order: Read in the Dictionary File, read in the MMS Extract File and aggregate the officers into categories (supply nodes), read in and process the ASR File into demand nodes, and create a node list consisting of the supply and demand nodes. Arc generation consists of connecting supply nodes to demand nodes resulting in the eligibility network G, and the creation of the proshare arcs to obtain the model network G'. Once completed, the model network is processed into the necessary data structures for ENET.

1. PROCESSING OF INPUT DATA

The Dictionary File is entered into the system and stored for future use. Then the MMS Extract File is read into OSGM-NPS. As each record in the MMS Extract File enters the system, its movement status is determined, and then it is

aggregated into the list of officer categories if possible. If a matching category does not exist, then a new one is created. Movement status is decided by a group of information that outlines the officer's current and future billets. The model generator decides if the officer will be allowed to move freely to any location to fill a billet (called a *mover*), restricted to a location but available for any billet at that location (called a *non-mover*), or fixed to a billet at a specific location (called a *fixed officer*).

Once all of the officers have been entered and aggregated into categories, the user can modify the categories by deleting officers, adding officers, or fixing the number of officers in a category. If all the officers are removed from a category, the category is removed from the model. If officers are added to a category that does not exist in the model, then a new category is created for the officers being added. MMOA-3's intent is to delete all Lieutenants in their initial generic training MOSs, and replace them with trained Lieutenants with the MOS they will have after training. This produces a more accurate model of what the Marine Corps officer population should be on the staffing goal date, in the following year, once the Lieutenants have graduated from their initial training schools. The resulting modified officer categories comprise a supply node list, where the number of officers in category i is s_i.

The ASR File is processed in two stages to create a list of demand nodes. Prior to this processing, the user is allowed to make modifications to ASR File records. The first processing stage takes each requirement from the modified ASR File and allocates it to an Officer Assignment Monitor (called *Monitor* for short). The Monitor is responsible for the actual assignment process that results in the transfer of an officer

from one duty station to another. The allocation to a Monitor is accomplished by adding an eight character code to each ASR File record. These codes are called Monitor Activity Codes (MACs), and each Monitor has a group of codes that label the requirements he is responsible for filling. The ASR File data comes into this first stage as a record containing BMCC, BMOS, BGRD and authorization; it leaves this first stage as a record, or records, with BMCC, BMOS, BGRD, MAC, and authorization. An ASR File record may be split into multiple records with the same BMCC, BMOS, and BGRD with the authorizations for the new records summing to the authorization of the original record. This feature allows requirements from the ASR File to be split between multiple MACs.

The second stage of demand processing is very similar to the first except that each requirement from the first stage output is now assigned a Billet Officer Description (BOD), SPL, and share percent. The nine character BOD together with the MAC are the unique link between the demand node and its eligibility rules. Again, a record from the output of the first stage of demand node processing may be split into two or more new records, identical except for the BOD and authorization. This splitting allows a requirement to be divided between two or more BODs. The demand nodes processed thus far in this discussion are referred to as *Chargeable* requirements.

The SPL is the priority class that the demand node belongs to and the share percent is 50 for all nodes representing fair sharing of shortages. Therefore, the set K has the values of the SPLs used in OSGM-NPS, which are $\{0,1,2,3,5\}$. The set $\{0,1,2,3,5\}$ represents priority classes one through five in the algorithm PENGEN and

the OSGP3 and OSGP4 models. Chargeable requirements are contained in SPLs {1,2,3,5} and prosharing is executed for all Chargeable requirements in OSGM-NPS making the set $K^P = \{1,2,3,5\}$. The SPLs of two, three, and five are those specified by the Marine Corps leadership as *excepted*, *priority*, and *other* commands, respectively (MCO 5320.12B, 1991). An SPL of one can only be assigned if the BMOS is in the list of critical MOSs in the Dictionary File. At the request of MMOA-3 at HQMC, OSGM-NPS allows the designation of a critical MOS-grade combination versus just a critical MOS. For example, instead of specifying that Intelligence Officers (MOS 0202) comprise a critical MOS, the Marine Corps can stipulate that Lieutenant and Lieutenant Colonel Intelligence Officers are a critical group in the officer population. This process puts all requirements matching the critical criteria into SPL one.

SPL zero is a special priority class set aside for officer requirements that are necessary, but do not contribute to the accomplishment of the Marine Corps mission. In any organization there are personnel that are in training or other positions that are required for operation, but do not directly contribute to the current productivity of the organization. The Marine Corps also has this classification of personnel, and they are called Patients, Prisoners, Transients, and Trainees (P2T2). OSGM-NPS refers to this classification as Non-Chargeable and Training requirements, and a set of these requirements is listed in the Dictionary File especially for this classification. They are not removed from the problem because there is such a small number of requirements that the bookkeeping necessary to remove them and account for them in the report writer is larger than simply including them in the model. Each requirement becomes a demand

node of the highest priority level with a special SPL of zero, and given an arc cost of zero since fit is not a concern. Because they are in the highest priority class, these requirements are filled prior to any other requirements. This results in the removal of the P2T2 personnel prior to staffing goals being produced for the Chargeable requirements, SPLs {1,2,3,5}.

The output from the second stage of demand node processing is a list of demand nodes that is ready to be added to the previously created list of supply nodes to create a formal node list. The node list consists of the node number, amount of supply or demand, and two node penalties for each node. The supply nodes are listed first by convention. The output of the algorithm PENGEN described in Section D of Chapter II contains the value for each node penalty.

Once the node list is complete, then the arc generation process is ready to begin. This process will create the eligibility arcs A and the proshare arcs A^P, concurrently. When this process is complete, the model network G′ will be loaded into the proper data structure for the solver. The following section describes this *arc generation* process.

2. ARC GENERATION

The arc generation process is accomplished in four phases. The first phase connects the officer categories that contain fixed officers to requirements with matching billets. The second phase connects the Non-Chargeable and Training requirements with eligible supply nodes. The third and largest phase connects the Chargeable requirements with eligible officer categories and creates each requirement's proshare arcs. Lastly, the model network G′ is loaded into the necessary data format for ENET.

The search for eligible officer categories to connect with Chargeable requirements is made efficient in the third phase of arc generation by using multi-dimensional pointers to the PMOS of the officer categories. The supply node list is sorted on the PMOS of the officer category. The eligibility rules specify eligible officer categories by the first digit, first two digits, first three digits, or all four digits of their PMOS. For example, an eligibility rule with PMOS of 03** would specify that all officer categories having a PMOS with the first two digits 03 are eligible for the requirement. Pointers are created for the indices of the beginning and end of each contiguous segment of the supply node list containing a PMOS eligible group of officer categories.

The first phase of arc generation is the connecting of fixed officer categories to their matching billets. The fixed officer categories are consider sequentially. For each category, the list of demand nodes is searched to find suitable requirements. Once a matching requirement having available billets is found, an arc is produced from the fixed officer category i to the matching requirement j and added to the set of fixed arcs $A^F \subset A$ with an arc cost of zero and upper and lower arc flow bounds equal to the number of officers that will fill billets in the matching requirement. Once the arc is created for the fixed officer category and matching requirement, the billets filled by the fixed flow are considered unavailable for subsequent searches for matching billets. This is the only case of a non-zero lower bound in the model.

Once all fixed officer categories have been processed, the Non-Chargeable and Training requirements are connected to eligible officer categories. These

requirements do not have multiple eligibility rules. Instead, they have a single eligibility rule of being eligible by pay grade and MOS of the requirement. For each Non-Chargeable and Training requirement, the list of supply nodes is searched to find officer categories with the same grade and MOS as the requirement. If the Non-Chargeable and Training requirement is actually a training requirement and a matching officer category contains non-movers, then the officer category's fixed MCC must be a training MCC for the category to be an eligible match. A list of training MCCs is given in the Dictionary File. Once an eligible match is found, an arc is created from officer category i to Non-Chargeable and Training requirement j and added to the set of arcs A with an arc cost of zero and the default arc flow bounds of $(l_{ij},u_{ij}) = (0,\Sigma s_i)$.

The third and largest phase of arc generation is the processing of the Chargeable demand nodes. Let E be the set of all eligibility rules from the Dictionary File. The set E is a sequence of subsets E_j, where E_j is the collection of eligibility rules for Chargeable demand node j such that $E = \bigcup E_j$ and each E_j is not necessarily mutually exclusive. For each Chargeable demand node j, the eligibility rules E_j are processed sequentially, with each rule searching the officer categories (supply nodes) for eligible categories. For each eligible officer category, an arc (i,j) is created from the matching category i to the demand node j, and added to the set of arcs A. Each arc (i,j) has the default flow bounds and cost c_{ij} equal to the Level Number (LN) for that eligibility rule.

The LN is a value from one to five[1], with one being the most suitable officer category for the requirement.

Once the first arc is created for a Chargeable demand node j, all of the proshare arcs for that node are created. Each proshare arc originates from the dummy node δ and terminates at a demand node j with arc cost $h_{\delta j}$ and arc flow bounds $(l_{\delta j}, u_{\delta j}) = (0,1)$. Upon creation, each proshare arc (δ, j) is added to the set of proshare arcs A^P. The proshare arc cost $h_{\delta j}$, is calculated in accordance with equation (2.17) using h^k_{max} (which is an output of the algorithm PENGEN) and the demand d_j with one modification: The value of the demand d_j is reduced by the solver subroutine prior to ENET being executed in order to transform all arcs with an $l_{ij} > 0$ into arcs with $l_{ij} = 0$. The modified demand at node j is $d_j' = d_j - \Sigma_{(i,j) \in RS(j)} l_{ij}$, where RS(j) is the set of arcs (i,j) entering node j, called the *reverse star* of node j. Since the value of d_j' is used in equation (2.17) versus d_j, the number of proshare arcs for node j is now d_j' instead of d_j, and the input d_j for PENGEN is d_j'. Details of the lower bound transformation will be discussed in the solver section of this chapter.

All data in OSGM-NPS is integer and the method in which the step-wise increasing penalties and proshare arc costs are generated creates two concerns. First, no penalty or cost can exceed the ubiquitous maximum 32 bit integer. This is easily verified. Second, the maximum value of any number computed by the solver must not

[1]OSGM-DSAI restricts $|E_j| \leq 5$; OSGM-NPS does not have this restriction, but a note of caution: As $|E_j|$ grows, so does c_{ij} and the magnitude of the cost-penalty structure.

exceed the maximum 32 bit integer. The only value of concern in the solver is the reduced cost of an arc.

The reduced cost is calculated by the sum of the costs of the forward arcs less the sum of the backwards arcs along the simple cycle caused by an entering arc in the rooted tree that represents the triangulated basis (Bradley, Brown, and Graves, 1977). The network simplex algorithm implemented by Bradley, Brown, and Graves creates an extra node, called the artificial node, connected to every node in the network $G' = (N',A')$. The arcs connecting G' to the artificial node are called artificial arcs and have arc costs that represent the node penalties. There are two distinct cases which must be considered for computing reduced costs. The first case is when the simple cycle does not include artificial arcs and the other is when it does. A worst case scenario for the first case is a cost of c'_{max} on the entering arc where c'_{max} is the maximum cost of all arcs $(i,j) \in A'$, a cost of c_{max} on the forward arcs in the cycle and zero on the backwards arcs in the cycle, and a cycle length of twice the minimum of the number of nodes and the number of arcs in the eligibility network G resulting in:

$$\text{reduced cost} \leq c'_{max} + \min\{|N^S|, |N^D|\}c_{max}. \tag{3.1}$$

The value of c'_{max} will be the value of the largest proshare arc cost h^1_{max} from PENGEN, and c_{max} is the maximum LN in the set of eligibility rules E.

A orst-case situation for the reduced cost in the second case is when the conditions are the same as the first case except the cost of the two artificial arcs are added to the problem. The worst-case cost of the forward artificial arc in the cycle is

some penalty p′ and the worst-case cost of the backward artificial arc is -p″ for some penalty p″. Let the value of $p^{max} = p_j^1$ from PENGEN for any $j \in N^D$, which by design is the largest penalty in the model, be a worst case value for p′ and p″. Thus,

$$\text{reduced cost} \le c'_{max} + \min(|N^S|, |N^D|)c_{max} + 2p^{max}. \qquad (3.2)$$

Integer overflow is a concern in OSGM-NPS. Using a representative set of input data, the right-hand side of equation (3.2) is 15,649,698,571 with a c'_{max} of 5,216,505,297; both exceeding the maximum 32 bit integer (2,147,483,647). Therefore, measures must be taken to prevent integer overflow. Five candidate techniques to help alleviate this problem are:

1. Solve the OSGP as a multi-objective linear program; an extension of the standard two phase linear programming algorithm.

2. Convert the cost-penalty structure to real numbers; staffing goals will remain integer.

3. Assume that 50% of the demand at each node will usually be filled. Under this assumption, all proshare arcs with a > $d_j/2$ for $j \in N_5^D$ can have the same cost $h^5_{max} \leftarrow h^5_{max}/2 + 1$. Carrying this through interatively for each higher priority SPL allows the cost-penalty structure (and maximum reduced cost) to be reduced by a factor of nearly eight.

4. The cost of the longest alternating path used in Chapter II and in equations (3.1) and (3.2) is a pessimistic bound. Using a representative set of input data where $|N^D| < |N^S|$, $|N^D| = 7307$, and $c_{max} = 5$ the value of $L_{max}c_{max}$ is 35,185. A better bound is $\Sigma_j \max_{i:(i,j)\in A, i':(i',j)\in A} \{c_{ij} - c_{i'j}\}$ which yields a value of 14,566 for this data. The use of the smaller number provides a tighter bound on the maximum reduced cost and tightens sufficient conditions from Chapter II. Also, it reduces the value of INC in PENGEN, and therefore, the magnitude of the cost-penalty structure.

5. Assume the value of L_{max} (half the length of the longest alternating path) is less than $\min\{|N^S|, |N^D|\}$. Lowering L_{max} reduces the initial value of INC in PENGEN, and therefore, reduces the entire cost-penalty structure.

OSGM-NPS uses the fifth method above to avoid integer overflow. OSGM-NPS's solution does not change when L_{max} is reduced to one. To illustrate this point, a test network was created with no Chargeable requirement having a demand more than ten. This allowed L_{max} to be $\min\{|N^S|,|N^D|\}$ without integer overflow. When L_{max} was set to one in the test network, the solution was unchanged. Therefore, a reasonable measure to avoid integer overflow is to reduce L_{max} in PENGEN by half if integer overflow might occur, re-execute PENGEN with the new smaller value of L_{max}, and continue this process until integer overflow is impossible. For the test data, L_{max} is reduced from 7,307 to 913 yielding an upper bound of 1,955,897,894 on reduced cost and with an observed maximum of 1,940,985,332.

During arc generation, information about each arc is stored in an arc list. The list contains an arbitrary arc number, tail node, head node, flow bounds, and arc cost. This arc list sorted in ascending head node order, along with the node list, is the output of the network generation process. However, ENET does not recognize the network in this data format. The solver requires that the network be represented in a reverse star adjacency list (e.g., GNET). To accomplish this a head node list H must be added to the model generator output. The index of this list is the node number of the head node j of an arc (i,j). H(j) is the index of the first tail node of the contiguous list of nodes adjacent to node j in the tail node portion of the arc list. Once H is created all model generator output is written to a disk for use as input to the solver. Total storage required is proportional to $|N'| + |A'|$. ENET produces a solution to OSGM-NPS in

the form of an arc list (i, j, x^*_{ij}) such that $x^*_{ij} > 0$, where x^*_{ij} is the optimal flow along arc $(i,j) \in A'$ in the solution.

C. SOLVER

ENET is a member of the GNET family of solvers for pure network flow problems developed by Bradley, Brown, and Graves 1977. ENET provides fast, memory-efficient solutions to large-scale pure network problems with elastic flow balance constraints. The arrays describing OSGM-NPS's network to ENET are written to disk by the model generator. The solver reads them into memory and executes a version of the network simplex algorithm to arrive at a solution. It writes to disk the objective function value z^*, and a list of the basic arcs and arcs non-basic at their upper bound in the format (i, j, x^*_{ij}). If an arc in the solution has node $i = \delta$, then the arc (δ,j) is a proshare arc and does not represent a staffing goal. However, if node $i \in N^S$, then x^*_{ij} represents the contribution of officer category i toward the staffing goal for requirement j. The sum of the flows along all arcs $(i,j) \in A$ into node j is the staffing goal for requirement j, called x^*_j.

There are arcs in the original network G' with $l_{ij} > 0$. ENET handles arc flow bounds of the form $(0,u_{ij})$. Therefore, all arcs with $l_{ij} > 0$ must be transformed to have $l_{ij} = 0$. This transformation is conducted within the solver module, but prior to the call of the solver subroutine. The standard transformation used by network solvers is $s_i = s_i - \Sigma_{(i,j) \in RS(j)} l_{ij}$, $d_j = d_j - \Sigma_{(i,j) \in RS(j)} l_{ij}$, $u_{ij} = u_{ij} - l_{ij}$, add a constant term of $\Sigma c_{ij} l_{ij}$ to the objective function, and lastly $l_{ij} = 0$ (Bradley, Brown, and Graves, 1977). Once the

solver has found a solution using the transformed data, the original values of l_{ij} are added back to the optimal flow $x^*_{ij}\ \forall\ (i,j) \in A^F$: $x^*_{ij} = x^*_{ij} + l_{ij}$.

The arc list solution is saved on disk for the report writer along with other output such as the list of supply nodes and demand nodes from the model generator. This information is all used by the report writer to produce the model's performance reports and output files required by the Marine Corps, which are described in the next section.

D. REPORT WRITER

The report writer takes output from the model generator and the solution produced by ENET and generates custom reports. MMOA-3 requires three of OSGM-DSAI's output files. OSGM-NPS produces these three files and other reports used to measure the model's performance during development. The three required output files are the Detailed Solution File, Detailed Solution File with SSNs, and the Unfilled Requirements File.

The Detailed Solution File has a record for every demand node (requirement) with the number of billets desired d_j, and then a record for every allocation made from category i to requirement j along with x^*_{ij}, sorted by requirement j. The Detailed Solution File with SSNs has a record for every officer not removed by the model generator with his SSN. If an officer is allocated by the model, then an SSN is randomly chosen from the SSNs of those officers aggregated into his category and listed in the file along with information for the officer category and information for the requirement. However, if an officer is not allocated, then the officer category information, along with

a randomly selected SSN from his category, is listed without any requirement information.

The Detailed Solution File with SSNs is not used extensively by MMOA-3. Its current use is to provide an answer to challenges to staffing goals. If a Monitor does not believe an officer exists in the population to create a staffing goal he must fill, then he challenges the staffing goal's validity. The Detailed Solution File with SSNs can be used to show the Monitor that the qualified officer does exist. It maybe that the Detailed Solution File with SSNs stems from DSAI's desire for OSGM-DSAI to have the capability to be an officer mobilization model, where actual assignments are necessary. Lastly, the Unfilled Requirements File is a list of all requirements left empty or partially filled in the solution such that $x_j^* < d_j$. Each under-filled requirement is listed along with the number of billets not filled which is $d_j - x_j^*$.

E. SOLUTION RESULTS

A sample data set was obtained from MMOA-3 that was used for the OSGM-DSAI run in July 1992 with a staffing goal date of October 1993. OSGM-NPS produced a solution with 95.63% of all requirements filled. This was marred by 245 officers (238 categories) not being connected to requirements and 50 billets (35 requirements) not being connected to officer categories due to a lack of eligibility. Another 598 officers that were connected to requirements were not allocated. No requirements were overfilled and no imaginary officers were created. SPLs were filled in priority order with SPL zero at 97.55%, SPL two at 99.45%, SPL three at 99.15%, and SPL five at 89.37%.

Each unfilled billet in SPL zero was investigated, and it was found that the unmet requirements were either not connected or there was a shortage of eligible officers. The July 1992 run of OSGM-DSAI did not utilize critical MOSs in the Dictionary File. Therefore, there were no requirements in SPL one. The solutions of OSGM-NPS and OSGM-DSAI are compared in Table I, where the results of the July 1992 OSGM-DSAI model execution and OSGM-NPS's results using the same input data are shown.

TABLE I
FILL COMPARISON

SPL	% Fill OSGM-DSAI	% Fill OSGM-NPS
0	96.36*	97.55
2	99.25	99.45
3	99.07	99.15
5	87.59	89.37
2, 3, and 5	94.64	95.41

OSGM-DSAI's results are from their Staffing Summary Report by SPL, except for SPL zero. Their Staffing Summary Report had a fill level of 100% for SPL zero. However, this was achieved by having the grades of Lieutenant Colonel, Major, and Warrant Officer filled in excess of 100%. This is impossible because Non-Chargeable and Training requirements are only eligible by grade and MOS. An investigation discovered that OSGM-DSAI "reports" un-allocated fixed officers in SPL zero. The

actual fill percent for OSGM-DSAI's Non-Chargeable and Training requirements of 96.36% was obtained from their Detailed Solution File, and is shown in Table I with an asterisk. OSGM-NPS's Detailed Solution File complies with OSGM-DSAI's "reporting" of un-allocated fixed officers in SPL zero. However, OSGM-NPS still reports the fill percent for SPL zero to be the percent of Non-Chargeable and Training requirements filled because it is a more germane statistic.

The performance comparison in Table I shows that OSGM-NPS provides a larger number of requirements filled in every SPL. This result is very favorable towards OSGM-NPS, but it is premature to say that OSGM-NPS's solution is "better" than OSGM-DSAI's solution until prosharing is compared. A comparison of the prosharing capabilities of OSGM-NPS versus OSGM-DSAI follows, and once this result is known, then a comprehensive comparison of the two solutions will be complete.

OSGM-NPS's performance, up through OSGP3, was measured by the total percent fill of the model and the percent fill of each SPL. By design, prosharing does not interfere with the fill of the model or fill in priority class order. Therefore, changes in the solution due to fair sharing should only be visible at the demand node level. This necessitates the development of a test statistic to verify that prosharing is having the desired effect. The most logical choice is the weighted Sum Squared Deviation (SSD) from total fill used in the derivation of the proshare arc cost function in Chapter II. Remembering that x_j^* is the staffing goal for requirement j and the demand at node j is d_j, then SSD_j is the weighted Sum Squared Deviation for demand node (requirement) j,

and SSD^k is the weighted Sum Squared Deviation for SPL k as shown in the following equations.

$$SSD_j = \frac{(d_j - x_j^*)^2}{d_j} \tag{3.3}$$

$$SSD^k = \sum_{j \in N_k^D} SSD_j \quad \forall k \in K^P$$

Since equation (3.3) is the same as equation (2.9) and prosharing is designed to minimize equation (2.9), then when prosharing is introduced in an SPL, the SSD^k should decrease, or at least not increase (worsen).

Prosharing was developed in OSGM-NPS one SPL at a time, beginning with the lowest priority SPL of five. Each subsequent stage in the development process added the next higher priority SPL until all SPLs in the set K^P were included. The results of prosharing development for OSGM-NPS are shown in Table II. The shaded cells are where there is no prosharing.

TABLE II
OSGM-NPS PROSHARING DEVELOPMENT RESULTS

Prosharing:	**None**	**SPL 5**	**SPL 3-5**	**SPL 2-5**
SSD^2:	7.83	7.83	7.83	7.67
SSD^3:	40.78	38.51	30.11	30.11
SSD^5:	498.33	269.35	266.15	268.26
Total:	546.94	315.69	304.09	306.04

The SSD dropped each time prosharing was introduced to an SPL, and when prosharing was introduced in SPL k, $SSD^{k'}$ for all $k' > k$ did not change significantly. The derivation of the proshare arc cost function in Chapter II is based on continuous variables. The proshare arc cost function in equation (2.17) truncates the ratio (a/d_j) to get an integer arc cost. This truncation introduces error such that SSD is not exactly minimized, and causes the fluctuations in the SPL five SSD seen in Table II. The results of OSGM-NPS's prosharing development are summarized as follows:

1. SSD^k dropped when prosharing was introduced into SPL k. Therefore, prosharing is having the desired fair sharing effect.

2. Since the SSD^k of lower priority SPLs does not change significantly when prosharing is introduced into a higher priority SPL, prosharing is conducted in each SPL independently of all other SPLs.

3. Total fill and fill in each SPL do not change when prosharing is conducted. Therefore, prosharing does not decrease the maximum fill or fill in SPL order.

OSGM-DSAI does not report on the effectiveness of prosharing. Hence, the Detailed Solution File from the DSAI July 1992 model execution was used to obtain SSDs for SPLs two through five. OSGM-DSAI's SSDs are compared with OSGM-NPS's SSDs in Table III. SPL zero is not included in Table III because prosharing is not conducted for Non-Chargeable and Training requirements.

TABLE III
PROSHARING COMPARISON

	OSGM-NPS	OSGM-DSAI
SSD^2	7.67	13.83
SSD^3	30.11	34.89
SSD^5	268.26	424.22
Total:	306.04	472.94

OSGM-NPS's prosharing outperforms OSGM-DSAI's prosharing in each SPL and in the overall model. OSGM-DSAI searches for alternating (augmenting) paths in which to move (swap) officers to improve fair sharing; which is evidently not as effective at fair sharing shortages of fill within an SPL as OSGM-NPS's proshare arcs.

OSGM-NPS's solution is superior to OSGM-DSAI's solution in every aspect. OSGM-NPS's fill percent and SSD for Chargeable SPLs are better than in OSGM-DSAI's July 1992 solution. Additionally, OSGM-NPS's fill percent and SSD in each SPL are better than in OSGM-DSAI's solution to the OSGP. Execution times for OSGM-NPS are discussed next.

F. COMPUTER IMPLEMENTATION RESULTS

An evaluation of the execution times of OSGM-NPS's version of ENET versus OSGM-DSAI's Allocator Module (DSAI, 1984) would be interesting. OSGM-DSAI's run times are not available for the July 1992 sample input data. However, the time necessary to execute the staffing goal process was obtained from MMOA-3 at HQMC (MMOA-3, 1993). The input data is up-loaded to the Dallas, Texas site of the CDC Cyber 175 either by modem (taking two to three hours) or by courier (requiring a half a day). Once the input data is ready in Dallas, OSGM-DSAI takes about 20 to 30 minutes to execute. If the model run is successful on the first attempt (reportedly a rare event, (MMOA-3, 1993)), then the output files are transferred back to HQMC by either modem (2 to 3 hours) or courier (half day).

On the AMDAHL 5995-700A the model generator took 60 seconds of CPU time (150 seconds wall clock time) and the solver took 114 seconds of CPU time (220 seconds wall clock time). The solver has been consistently quick. The execution time of the report writer is omitted because it depends on the number of reports requested. A full OSGM-NPS execution with all reports takes approximately 20 minutes of wall clock time, half of which is disk access time for the report writer, with an average number of users on the mainframe. The network solved has 717,694 arcs and 18,085 nodes, and ENET took 88,615 pivots to solve this problem.

OSGM-NPS has been compiled and executed on a 80486 33Mhz Compaq Personal Computer (PC) with 52 megabytes of RAM. It was compiled using the SVS FORTRAN compiler with an Intel C^3 DOS Extender (SVS, 1991). The DOS extender allows

OSGM-NPS to access the amount of RAM necessary for it to execute on a PC. The model generator executed in 264.85 seconds (4.14 minutes), and the solver executed in 292.5 seconds (4.87 minutes).

OSGM-NPS is implemented in standard ANSI FORTRAN-77. Therefore, the algorithms are portable to UNIX workstations and PCs. Since OSGM-NPS uses less than 64 megabytes of RAM, the concern for memory limitations in DSAI's Commercial Off-the-Shelf (COTS) software analysis is not applicable (DSAI, 1992).

IV. CONCLUSIONS AND RECOMMENDATIONS

OSGM-NPS has been shown to provide a better solution to the OSGP than OSGM-DSAI, and it is not plagued by OSGM-DSAI's time-consuming and high cost execution on an off-site mainframe computer. OSGM-NPS is not restricted to a particular computer and, in fact, a desktop computer will do. OSGM-NPS is designed to be executed at HQMC by the Marine Corps, not for them. Conclusions regarding the development and testing of OSGM-NPS are summarized below along with recommendations for further research.

A. CONCLUSIONS

OSGM-NPS provides a better solution than OSGM-DSAI to the OSGP. OSGM-NPS fills more requirements and has better fair sharing (lower *Sum Squared Deviation* (SSD)) than OSGM-DSAI in each Staffing Precedence Level (SPL) and in the entire model. OSGM-NPS provides a faster solution to the OSGP with a qualitative improvement in responsiveness; the time necessary to get a usable solution is minutes not a day or two. OSGM-NPS is less expensive to operate than OSGM-DSAI's model; a one time purchase of a computer (estimated at $9000 for a suitable PC) will be the entire computing hardware cost. "What-if" scenarios and multiple executions per year can be done at little or no extra cost; Monitors will have a more accurate and up-to-date view of how officer assignments should be made.

This thesis refutes the findings and concerns of DSAI's Commercial Off-the-Shelf (COTS) software analysis: Both the concerns of memory limitations and execution times are moot with the advent of OSGM-NPS. OSGM-NPS can operate on a desktop computer or workstation at HQMC versus a costly off-site mainframe, and it will produce a better solution to the OSGP than OSGM-DSAI at a substantially reduced cost.

B. RECOMMENDATIONS

The OSGM-NPS computer model created during this research should be considered a prototype for a replacement to OSGM-DSAI. OSGM-NPS has been executed on a 80486 Compaq PC. A user-friendly PC environment should be developed to simplify the data preparation, solution, and review process making the model easier to manage for MMOA-3 and the Monitors. (Work is underway on this topic.)

The format of the Dictionary File should be examined and changed to simplify the work required by MMOA-3 and streamline the staffing goal process. The introduction of a new data format based on the eligibility network, and a user-friendly data preparation system would streamline the model preparation process. If the largest requirement in the OSGP grows in size such that integer overflow becomes a problem, the arc costs and penalties in OSGM-NPS could be changed to floating point values, the model could be solved using a hierarchical multi-objective algorithm, or the 50% proshare arc cost method could be used concurrently with the reduction of L_{max}. None of these options are difficult to implement.

The elastic network flow concepts developed in OSGM-NPS should be considered for the other allocation/assignment problems conducted by Manpower and Reserve Affairs at HQMC such as the Enlisted Staffing Goal Model and the Enlisted Assignment Model. These problems are larger than the OSGP, and therefore, the structure of the model generator might differ from OSGM-NPS and the memory requirements would increase. However, the same basic methodology used in OSGM-NPS should apply, and these larger models could be solved quickly and *optimally* without proprietary algorithms that create an undue dependency on a civilian contractor.

APPENDIX A

OSGM-NPS MODEL LIMITATIONS

OSGM-NPS utilizes the users manual that Decision Systems Associates, Inc. provided the Marine Corps for their model. Many features included in the current model are not used, and therefore they are not included in OSGM-NPS. The following is a list of the features in DSAI's model that are not included in OSGM-NPS.

Share Percent: The share percent is a number from one to 99 that denotes proportionate sharing among demand nodes of the same SPL. Its default value is 50, to mean fair sharing of shortages of fill among demand nodes of the same SPL. The use of the share percent has some staffing policy considerations. It was designed to allow the user to designate a percentage of relative fill compared to billets of the same SPL, more commonly called unfair sharing. A three step process, it first requires close examination of the model's output executed with fair and/or unfair sharing, then the user re-specifies the share percent for a billet definition (E2 card) to change the sharing scheme, and then the user executes the model again with the desired new sharing scheme. This is a very costly and time consuming process. Marine Corps staffing policies are expressed as SPLs set forth in Marine Corps Order 5320.12B dated 14 May 1991 from the Deputy Chief of Staff for Manpower and Reserve Affairs. Using the share percent

would be a further subdivision of priority of fill from the order, and could be construed as a violation of the directive. The combination of these obstacles to the use of the share percent precludes any value other than the default. Incorporation of the share percent should require only modifications of the proshare arc costs.

Allocation of Percent Remaining (D1 and E2 Cards): In the processing of the Authorized Strength File into demand nodes the user has the capability to make sub-authorizations. This takes a record from the ASR input file and splits it into two or more identical records with the sum of the new records being the original authorization. OSGM-DSAI allows two methods to execute this feature. One is the allocation of an integer amount of authorized strength to a new record, and the other is allocate a percent of the remaining authorization. The Marine Corps utilizes only the integer feature and hence that is the only method OSGM-NPS allows.

Excess Distributions (E4 Card): This optional feature is used to create Non-Chargeable demands in excess of the SPL zero Non-Chargeable and Training requirements. The user's manual stresses that these cards should not be incorporated in the initial model execution, only on subsequent executions if needed. In practice, subsequent executions are not made. Once the model is successfully executed, the resulting staffing goals are used with no more fooling around. This could be handled.

Default First Term Attrition Rates (F1 Card): This information is present in the sample Dictionary file, but the values are zero. These values are used to randomly remove officers from the MMS extract input data to simulate normal attrition. This

feature is not used because the user removes officers that should separate prior to run time.

Primary MOS First Term Attrition Rate Specification Cards (F2 Card): This is an optional feature that compliments the Default First Term Attrition Rates. This allows the user to override the default attrition rates with a rate specific by rank and MOS. This is not used for the same reasons as the F1 card.

Date 1/Date 2 Specification Card (F4 Card): Date 1 and Date 2 information is not present in the input data. An explanation of its use is not contained in the OSGM User's Manual V1.00. The feature is not currently used by MMOA-3, and is therefore not included.

Women/Reserve/Retired Limits (F5 Card): This feature was used when OSGM-DSAI produced mobilization staffing goals. Since a network-based officer mobilization model has been procured by the Marine Corps, this feature is unnecessary in the peacetime OSGM-NPS model.

Component Codes to Fix Officers (F6 Card): This is an optional card that is a list of two digit component codes. Each officer has a component code, and if an officer's code matches a code in this list, then he is fixed to his current location during the model run. This feature is not utilized by the user.

Component Codes Which Render an Officer Ineligible for Assignment (F7 Card): This is optional card that is a list of two digit component codes. Each officer has a component code, and if an officer's code matches a code in this list, then he is

removed from the model because he is ineligible for assignment. This feature is not utilized by the user because these officers are extracted prior to run time.

Output Files: The three output files used by MMOA-3 in the creation of custom reports are generated by OSGM-NPS: The Detailed Solution File, the Detailed Solution File with SSNs, and the Unfilled Requirements File. All other output files and printed reports are not produced. If OSGM-NPS is implemented, its output can be tailored to any format desired by the user. OSGM-NPS currently has all reports necessary to evaluate the model's performance.

APPENDIX B

A. DEFINITIONS

Additional Military Occupational Specialty (AMOS): An MOS for which the Marine is trained, but the MOS does not represent the training he received for his primary duties.

Authorized Strength Report File: A list of job positions, called *billets*, that the Marine Corps desires to fill. Positions are listed by billet MCC, billet MOS, billet grade, and the authorized strength for the billet.

Billet: A job position in the Marine Corps specified by MOS, grade, and location.

Billet Officer Description (BOD): A nine character code, which along with the MAC uniquely links a Chargeable requirement with its eligibility rules. The term is also used in OSGM-DSAI as the generic name for eligibility rules.

Chargeable Requirement: Those requirements that are directly accountable against a unit's authorized strength.

Dictionary File: Referred to as "the Dictionary." This is all information necessary to execute OSGM-NPS not contained in the ASR and the MMS Extract files. The file contains a list of valid MOSs, modifications to the ASR and MMS Extract files, information to process the ASR into a list of demand nodes, and the eligibility rules to connect officer categories to manpower requirements.

Duty Limitation: Sometimes referred to as "restrictions", every officer is either a Limited Duty Officer (LDO) or an Unrestricted Officer. LDOs are specially qualified officers that are restricted to certain types of billets so as not to waste their special training. Examples of LDO billets are Maintenance Officers and Personnel Officers. The majority of officers are Unrestricted.

Experience Level: A term used solely in the Officer Staffing Goal Model, experience level has two values, experienced and inexperienced. The determination of experience level is set by MMOA-3, and is a function of the amount of time the officer has been at his current grade and MOS.

Grade: The lineal status that a service member possesses in relationship to all other service members. Military members are paid and receive responsibility in accordance with their grade. The term grade is synonymous with rank in most cases. Sometimes an officer may be of a different rank than he is paid so he may perform a particular job. An example is a Captain who is selected, but not yet promoted to Major, who may command a Recruiting Station wearing the rank of Major, but who will still be paid as a Captain. In this situation the officer has been "frocked" to Major to fill the billet.

Manpower Management System (MMS): The computer data base system used in the Marine Corps to store all data on its personnel.

Manpower Management System (MMS) Extract File: An extract from MMS containing a record for each officer on active duty.

Military Occupational Specialty (MOS): A 4 digit number representing the job or specialty of a Marine.

Monitor Activity Code (MAC): An eight character code that tags each record of the ASR file for a particular Monitor. For example, all fixed wing aviator requirements in the ASR may be tagged with a MAC of MMOA2FIX to represent the aviation Monitor who is responsible for their staffing goals.

Monitored Command Code (MCC): There are many commands in the Marine Corps. They span the continental U. S. and overseas. To organize billets at these commands for assignment purposes, each command in the Marine Corps in need of assignment consideration receives a three character code. The code that may consist of any number or alphabetical characters.

Mover: An officer category in OSGM-NPS whose officer are free to move to any billet for which they are eligible.

Non-Chargeable and Training Requirement: The Marine Corps officer overhead, representing the Patients, Prisoners, Transients, and Trainees (P2T2). Demand not counted against the authorized strength. Specified in the E3 cards of the Dictionary File and given an SPL of zero.

Non-Mover: An officer category in OSGM-NPS that is restricted to billets having a specific MCC.

Officer Assignment Monitor (Monitor): An officer whose duties are to assign other officers to specific billets.

Officer Category: A collection of officers in OSGM-NPS having the same PMOS, AMOSs, grade, duty limitation, experience level, sex, location, and duty status.

Duty Status of an Officer: Three possible values are active duty, reserve, and retired. Every officer considered by OSGM-NPS is in one of these three states.

Patients, Prisoners, Transients, and Trainees (P2T2): These are the Non-Chargeable and Training Marines. They do not count against a unit's authorized strength.

Primary Military Occupational Specialty (PMOS): An MOS that is the primary job of a Marine.

Share Percent: The method in which OSGM-NPS distributes unmet officer requirements in the same Staffing Precedence Level. Starts at 1 and goes to 99, with 1 being the most important and 99 the least important. The following two statements are the only guarantee of the share percent's actions: All requirements in an Staffing Precedence Level having the same share percent receive the same proportion of fill if possible. Requirements within an Staffing Precedence Level having larger share percents receive a larger proportion of the available officers than requirements with smaller share percents.

Staffing Precedence Level (SPL): The priority placed on the filling of a billet as compared to all other billets.

Staffing Goal: A numerical target by MCC providing distribution by grade and MOS reflecting the current inventory and assignment policies. Staffing goals change continuously and reflect changes in both the chargeable inventory and authorized strength. A computer model prepares the goals which compare the chargeable inventory grade and skill mix to the Marine Corps' authorized billet mix.

Staffing Goal Date: The future year and month for which the OSGM-NPS model projects staffing goals, usually October of the next calendar year.

B. ACRONYMS

Acronym	Definition
AMOS	Additional MOS
ASR	Authorized Strength Report
BGRD	Billet Pay Grade
BMOS	Billet MOS
BOD	Billet Officer Description
CMCC	Current MCC
FMCC	Future MCC
HQMC	Headquarters Marine Corps
MAC	Monitor Activity Code
MCC	Monitored Command Code
MMOA	Officer Assignment Branch, Manpower, HQMC
MMS	Manpower Management System
MOS	Military Occupational Specialty
OSGM-DSAI	Officer Staffing Goal Model-Decision Systems Associates
OSGM-NPS	Officer Staffing Goal Model-Naval Postgraduate School
OSGP	Officer Staffing Goal Problem
P2T2	Patients,Prisoners,Transients, and Trainees
PMOS	Primary MOS
SPL	Staffing Precedence Level
SSN	Social Security Number

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